Chapter 5

Prospects of Gasoline Compression Ignition (GCI) Engine Technology in Transport Sector

Vishnu Singh Solanki, Nirendra Nath Mustafi and Avinash Kumar Agarwal

Abstract Compression ignition (CI) engines are mainly fuelled by diesel-like high cetane fuels, and they have higher overall efficiency due to higher compression ratio compared to their spark ignition (SI) engine counterparts. However, modern diesel engines are more expensive, complicated, and emit high nitrogen oxides (NOx) and particulate matter (PM). Simultaneous control of soot and NOx emissions in diesel engines is quite challenging and expensive. Thermal efficiency of SI engines, on the other hand is limited by the tendency of abnormal combustion at higher compression ratios therefore use of high octane fuel is essential for developing more efficient higher compression ratio SI engines in near future. In the foreseeable future, refineries will process heavier crude oil to produce relatively inferior petroleum products to power the IC engines. Also, fuel demand will shift more towards diesel and jet fuels, which would lead to availability of surplus amounts of low octane gasoline with oil marketing companies, with little apparent use for operating the engines. This low octane gasoline will be cheaper and would be available in excess quantities in foreseeable future as the demand for gasoline will further drop due to increase in the fuel economy of modern generation gasoline fuelled vehicles. For addressing these issues, Gasoline compression ignition (GCI) engine technology is being developed, which is a futuristic engine technology that takes advantage of higher volatility, and higher auto-ignition temperature of gasoline and higher compression ratio (CR) of a diesel engine simultaneously to take care of soot and NOx emissions without compromising diesel engine like efficiency. GCI engines can efficiently operate on low octane gasoline (RON of ~70) with better controls at part load conditions. However cold starting, high CO and HC emissions, combustion stability at part load, and high combustion noise at medium-to-full load operations are some of the challenges associated with GCI engine technology. Introductory sections of this chapter highlights future energy and transport scenario, trends of future fuel demand, availability of low octane fuels and development in advanced engine combustion technologies such as HCCI, PCCI, RCCI, and GDI. GCI engine development, its combustion characteristics and controls are discussed in detail. Particular emphasis is given to the effect

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of various control strategies on GCI combustion, performance and emissions, fuel quality requirement and adaption of GCI technology in modern CI engines. In addition, this chapter reviews initial experimental studies to assess the potential benefits of GCI technology.

Keywords IC engines · GCI engine technology · Combustion control · Low octane gasoline · Oxides of nitrogen (NOx) · Particulates

5.1 Introduction

Growth of transport sector plays a vital role in overall development of the country. At present, ~99% of global transport fleet is powered by internal combustion (IC) engines, in which, liquid petroleum products power ~95% vehicles. This trend would continue to rise due to high energy density, easy processing and transportation of liquid petroleum fuels, and availability of desired infrastructure (Kalghatgi 2018). By the end of 2014, ~910 million passenger cars and ~330 million commercial vehicles were available in the market (Statista 2016). In coming decades, these numbers would continue to rise at a growth rate of 1%, especially in non-OECD (Organization for Economic Co-operation and Development) countries like India and China (U.S. Energy Information Administration 2016; World Economic Forum 2016; Exxonmobil 2019). Transport sector consumes ~20% of global energy and is responsible for ~23% of global carbon di-oxide (CO_2) emissions. However, overall GHG emissions from transport sector are only ~14%, which is comparable to GHG emissions from farming and dairy Industry (U.S. Energy Information Administration 2016; Outlook 2017; IPCC 2019). Figure 5.1 shows sector-wise global GHG emissions.

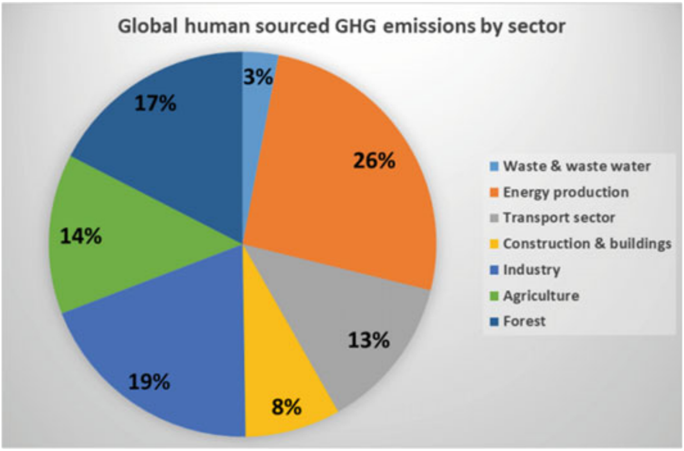


Fig. 5.1 Global anthropogenic GHG emissions sector-wise (*Web Source* http://www.climate-change-knowledge.org/ghg_sources.html)

Global daily consumption of petroleum products in terms of million barrels of oil equivalent (BoE) by the end of 2017 is presented in Table 5.1 (International Energy Agency 2017). By 2040, energy demand for non-OECD countries will be 40% higher than today's demand. Refineries would have no choice but to utilize residual heavier crude oil to meet such a massive demand of fuel in future.

However, now the question is that, is there enough reserves of oil so that the growth of the IC engine will not be affected by the oil demand? Mainly supply of oil depends on the discoveries and efficiency of oil extraction. Since last some decades, the availability of oil is more than the demand. Figure 5.2 (BP Statistical Review of World Energy 2017) shows evolution of oil reserves and the ratio of oil reserves-to-annual production between 1980 and 2010.

Table 5.1 Daily global oil demand at the end of 2017 (International Energy Agency 2017)

	Million Barrels of oil Equivalent (BoE)			Energy, exa-joules	Fuel volume, billion liters
	OECD	Non-OECD	Total		
Gasoline	14.5	11.3	25.8	0.158	4.85
Diesel/Gasoil	13.7	14.6	28.4	0.174	4.83
Jet/Kerosene	4.3	3.2	7.5	0.046	1.27
Residual Oil	2.1	5.4	7.5	0.046	
Others[a]	12.8	16.1	28.9	0.177	
Total	47.4	50.7	98.1	0.601	

[a]Other includes naphtha, LPG and ethane
1 exajoule = 10^{18} Joules = 277,778 GWh = 163.4 million BoE

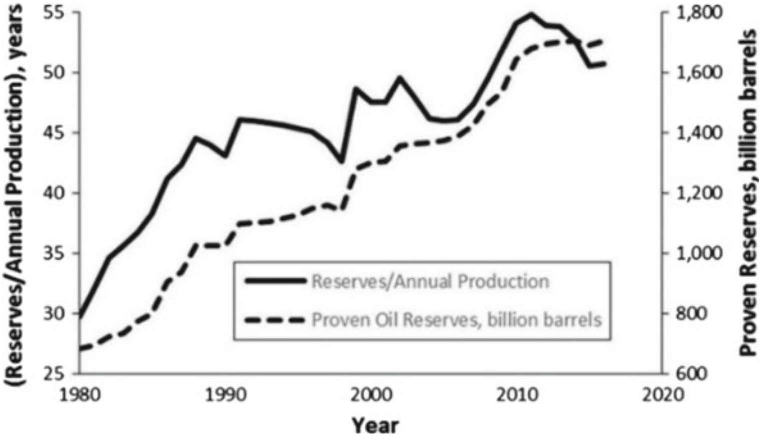


Fig. 5.2 Oil reserves-to-annual production ratio and evolution of proven oil reserves (BP Statistical Review of World Energy 2017)

In 1980, oil reserve capacity was 29 years, which increases to 50 years by 2016. Discoveries and efficient oil extraction techniques would further increase the oil supply in future, hopefully. In 2007, according to worldwide recovery factor, only a small fraction (~27%) of oil could be recovered from the oil wells (Sandrea and Sandrea 2007). Recovery rate can be further enhanced by advanced technologies such as injecting fluid and gas (e.g., CO_2). Introduction of alternative fuels such as shale oil and gas, methanol, and DME will also help the availability of fuel resources for powering IC engines based transport system. Hence the supply of petroleum products will not constrain the growth of engines in foreseeable future.

Currently gasoline-fueled light-duty vehicles (LDV) consume ~44% of total transport energy (U.S. Energy Information Administration 2016). It is easier to replace gasoline-fueled LDV's by the electric, hybrid, fuel-cell vehicles. In future, passenger cars will be travelling relatively shorter distances due to development of smart cities (U.S. Energy Information Administration 2019; World Energy Outlook 2011; U.S. Energy Information Administration 2013; International Energy Agency 2015; Kalghatgi 2014). Hence dependency on gasoline will be relatively lesser in future. Heavy-duty engines will be fueled by more clean fuels than today's diesel. Therefore transport fuel demand domination will shift from light-duty cars to heavy-duty commercial vehicles such as trucks, buses, rail, and marine engines in near future (World Energy Outlook 2011). It would mean that demand for diesel would be higher than that for gasoline in foreseeable future. Projections of gasoline, diesel, and jet fuel demands in the coming decades are captured in Fig. 5.3 (BP Statistical Review of World Energy 2014).

This transition of transport fuel may create abundance/surplus low octane gasoline in refineries and oil marketing companies, which can be used for mitigating the imbalance in future demand for fuel for heavier commercial transport, that uses diesel as of now.

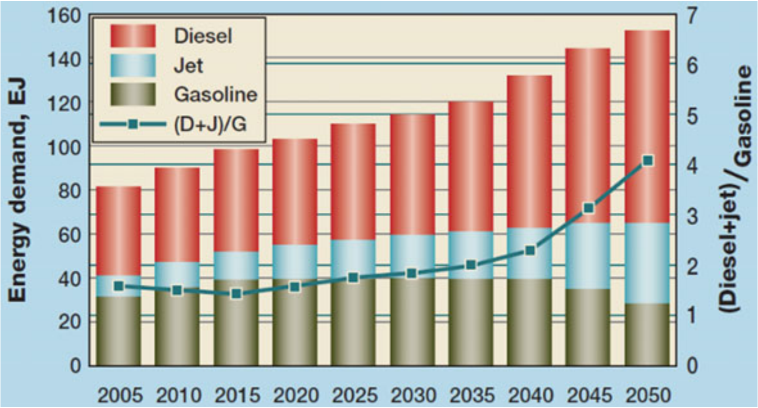


Fig. 5.3 World Energy Council projections for gasoline, jet-fuel and diesel demand up to 2050 (BP Statistical Review of World Energy 2014)

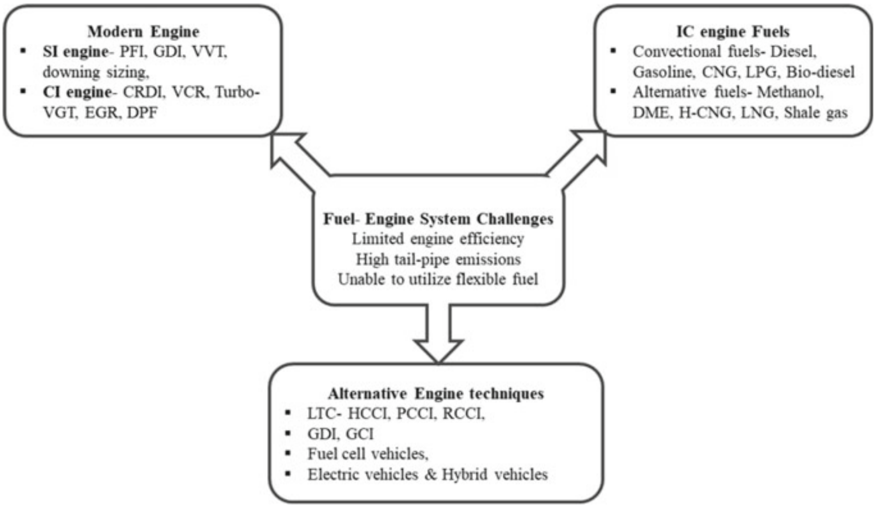


Fig. 5.4 Opportunities and challenges of the fuel-engine system in near future

Current IC engines generally operate on two conventional combustion modes namely spark ignition (SI) and compression ignition (CI) modes. SI engines mainly operate under stoichiometric conditions and utilize 3-way catalytic converters to control high emissions of hydrocarbons (HC), carbon monoxides (CO) and nitrogen oxides (NOx). SI engines would require improvement in fuel's octane rating for further efficiency improvement, which would increase demand for higher octane gasoline. Refineries would therefore require additional investments to produce high-octane gasoline from the heavier crude oil, which is going to be energy-intensive and would entail higher greenhouse gas (GHG) emissions during fuel production process. Opportunities and challenges for the fuel-engine system in near future are captured in Fig. 5.4.

Modern diesel engines are more efficient and emit lower tail-pipe CO and HC emissions than SI engines, but emit higher PM and NOx, which are toxic to human health and the environment. For controlling NOx and PM emissions simultaneously, a diesel engine requires advanced exhaust gas after-treatment system such as diesel particulate filter (DPF) and SCR system, which would increase system complexity and total cost of the vehicle. PM and NOx emissions from CI engines can be controlled by enhancing the fuel-air mixing (turbulence) before the start of combustion (SoC). Gasoline has higher volatility and longer ignition delay than diesel. Higher resistance to auto-ignition allows gasoline more time for mixing with air before the start of combustion (SoC), and higher volatility promotes homogenous mixing of fuel and air. In summary, greater stock of cheaper low octane rating fuel would be available in the market in future to power IC engines, which could be used to reduce GHG emissions as well. GCI engines can operate on low-octane gasoline with a substantial reduction in PM and NOx emissions without compromise in engine efficiency. Introduction of this new GCI engine-fuel system would reduce capital investments in the refinery, well-to-wheel (WTW) emissions, and total cost of vehicle ownership (Kalghatgi and Johansson 2018).

5.2 Conventional Fuels and Fuel Properties

IC engines mainly operate on petroleum-based liquid or gaseous fuels, which are processed from the crude oil in refineries. As crude oil temperature increases in a fractional distillation column, gas comes out from the crude oil, which is called liquid petroleum gas (LPG). Straight run gasoline (SRG) is recovered between 20 and 200 °C, and diesel is recovered between 160 and 380 °C. The term 'naphtha' is used for the product that lie close to the gasoline boiling temperature range. 40–60% of the petroleum products (by weight) are heavy components, with boiling range higher than 380 °C. Heavy components are further cracked down to light hydrocarbons for improving their cetane or octane rating. Many additives are added to refined products to meet fuel specifications. In addition to petroleum-based fuels, biofuels, alcohols, and other gaseous fuels (such as NG, biogas etc.) are used to power IC engines (Kalghatgi and Johansson 2018). Important fuel properties of diesel and gasoline are listed in Table 5.2 (Web Source: http://large.stanford.edu/courses/2010/ph240/veltman2/docs/Propertiesoffuels.pdf).

Some critical fuel properties, which significantly influence engine combustion, performance and emissions, are discussed.

Auto-ignition Temperature and Volatility These are two crucial fuel properties that play a vital role for air-fuel mixture homogeneity thus strongly influence engine combustion characteristics. Gasoline has higher auto-ignition temperature and volatility than diesel, which facilitates better homogenous mixtures of gasoline.

Octane/Cetane Number Cetane and octane rating measures the ability of spontaneous ignition of fuel. Octane rating expresses gasoline's ignitability and Cetane rating for diesel. In other words, octane rating measures the strength of resistance to auto-ignition/pre-ignition of gasoline. Higher octane number provides greater resistance to auto-ignition/pre-ignition under high combustion temperature and pressure, which enhances combustion efficiency in gasoline engines. Cetane number measures the ignition delay period before the start of combustion (SoC). High cetane number means a shorter delay period, resulting in better combustion efficiency in diesel engines. High octane fuel has a low cetane rating and vice versa.

Molar Mass Gasoline has lower molecular weight compared to diesel (gasoline: 100–105 kg/kmol; diesel: 200 kg/kmol). Due to lower molecular weight, diffusion rate of gasoline is higher than diesel, which helps in reducing tailpipe emissions.

Latent Heat of Vaporization Gasoline has higher latent heat of vaporization than diesel (gasoline: 375 kJ/kg; diesel: 250 kJ/kg). Higher heat of vaporization of gasoline

Table 5.2 Comparison of diesel and gasoline specifications (*Web Source* http://large.stanford.edu/courses/2010/ph240/veltman2/docs/Propertiesoffuels.pdf)

Property	Unit	Diesel	Gasoline
Chemical formula		C_8–C_{25}	C_4–C_{12}
Fuel carbon	wt%	84–87	85–88
Fuel hydrogen	wt%	16–33	12–15
Molecular weight		200	100–105
Density at 15 °C	kg/m^3	810–890	720–780
Lower heating value	MJ/kg	42.7	43.4
Net calorific value	MJ/l	36	32
Research octane number (RON)		–	90–100
Cetane number		40–55	5–20
Boiling temperature	°C	187–343	26–225
Reid vapor pressure	psi	0.2	8–15
Viscosity (at 15 °C)	Centipoise	2.6–4.1	0.37–0.44
Auto ignition temperature in air	°C	210	280
Latent heat of vaporization (at 1 bar)	kJ/kg	250	375
Minimum ignition energy (at $\varphi = 1$)	mJ	0.23	0.8
Stoichiometric air/fuel ratio		14.6	14.7
Flammability limits	vol.%	0.5–7.5	1.4–7.6
Flash point	°C	73	−42

provides better cooling of intake charge compared to diesel, leading to improved engine efficiency and power.

Lower Heating Value The calorific value of gasoline (on mass basis) is slightly higher than diesel (gasoline: 43.4 MJ/kg; diesel: 42.7 MJ/kg). However, diesel has higher density than petrol (gasoline: 750 kg/m^3; diesel: 835 kg/m^3) and have ~12.5% higher energy content per unit volume (gasoline: 32 MJ/m^3; Diesel: 36 MJ/m^3). Apart from difference in energy density, diesel engines are 20% more efficient than gasoline engines and hence more gasoline quantity will be required to be injected for achieving the same power output from a diesel engine.

Lubricity and Viscosity Gasoline provides lower lubrication than diesel and injection of gasoline at high-pressure results in more wear and tear of the fuel injection equipment. Additionally, viscosity of gasoline is also lower than diesel. Therefore suitable additives will be required for utilization of gasoline in CI engines.

5.3 Gasoline and Diesel Spray Characteristics

Fuel spray characteristics are important since they play a vital role in mixing of fuel with air in the combustion chamber (direct injection engines) or in the intake port (port fuel injection engines). Macroscopic spray characteristics include spray penetration length, spray cone angle, spray area and microscopic spray characteristics include droplet size-velocity, and size-number distributions.

Fuel properties significantly affect spray characteristics and consequent fuel-air mixing characteristics. Spray penetration length of gasoline was reported to be shorter than diesel spray due to lower fuel density and viscosity but higher volatility (higher evaporation rate) of gasoline (Kim et al. 2013). It helps in early direct injection of gasoline in CI engines without the wall impingement. However gasoline spray has larger cone angle than diesel sprays due to higher Reynolds number. These effects are more dominant in case of increased fuel injection pressure (FIP) as shown in Figs. 5.5 and 5.6. Results from other studies (Payri et al. 2012) suggested that momentum flux

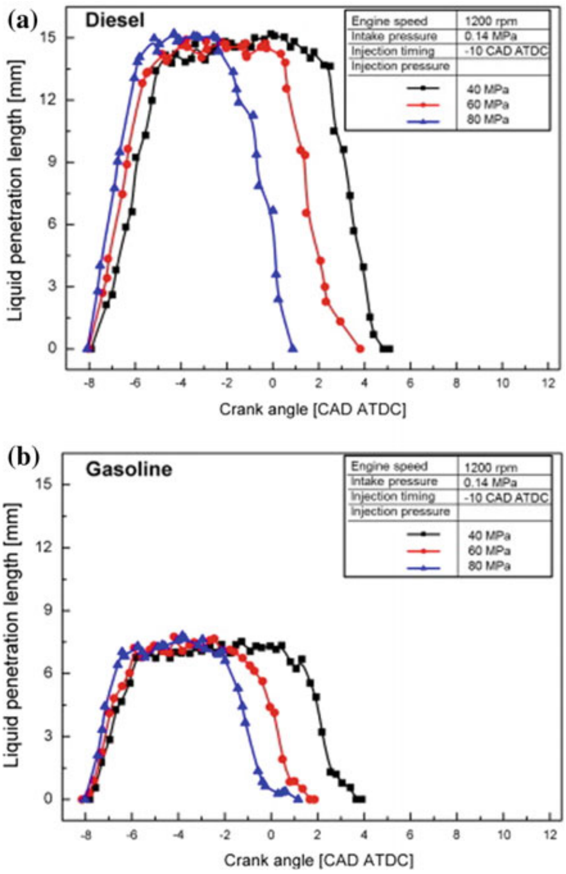


Fig. 5.5 liquid penetration length traces for **a** diesel and **b** gasoline sprays at different fuel injection pressures and fixed injection timing of −10 CAD aTDC in evaporative conditions. (Kim et al. 2013)

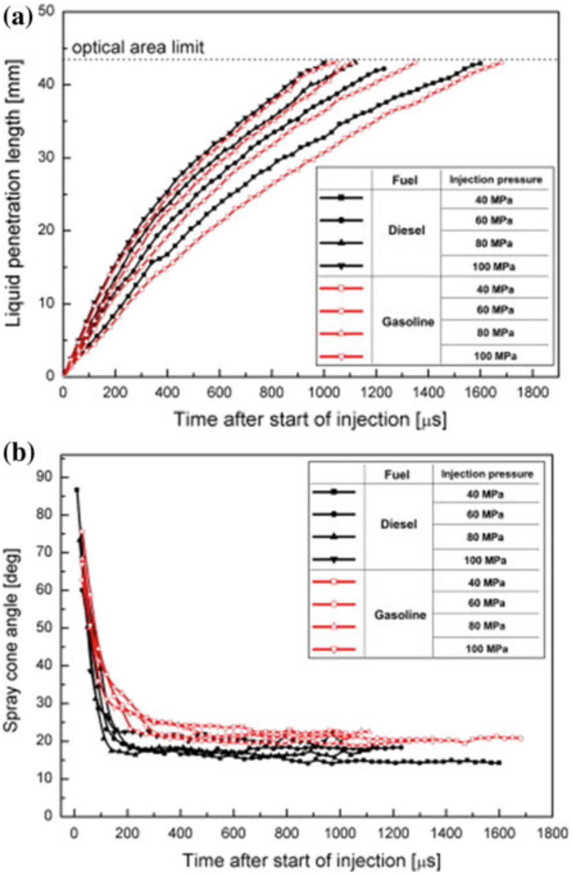


Fig. 5.6 **a** Spray penetration length, **b** spray cone angle for gasoline and diesel at different fuel injection pressures according to the time after the start of the injection in non-evaporative conditions (Kim et al. 2013)

was similar for both gasoline and diesel sprays and was independent of fuel density and injector hole diameter.

5.4 Engine Combustion

SI engines are commonly preferred for light-duty applications and currently, ~80% of global transport vehicles operate on SI engines, whereas CI engines are mostly preferred for heavy-duty vehicles such as bus, heavy duty truck, and off-road machinery (OPEC, Organization of the Petroleum Exporting Countries 2013). In SI engines, premixed fuel-air charge is supplied into the combustion chamber, and a spark plug is used as an ignition source for initiating the flame propagation. However, in most diesel engines, fuel is directly injected into the combustion chamber at a high temperature near TDC, just before the end of the compression stroke. Unlike SI engines, ignition initiates in diesel engines by auto-ignition of combustible charge, once it reaches its self-ignition temperature (Kalghatgi and Johansson 2018). CI engines are characterized by higher compression ratio (CR) and zero throttling losses (Stone 2012). Compression of fuel-air mixture increases pumping losses in a SI engine (OPEC, Organization of the Petroleum Exporting Countries 2013; Heywood 1988; Stone 2012; Boot 2016). SI engine efficiency is usually limited by abnormal combustion or knocking, which is mainly due to pre-ignition of end-gas before flame front reaches to it. SI engines normally operate under stoichiometric to slightly rich fuel-air mixtures, whereas diesel engines always operate under lean condition. Effectiveness of SI engines at low load conditions is inferior because of increase in pumping losses. IC engines are facing huge challenges now-a-days for stringent emission norm compliance. Researchers are focusing on advanced engine combustion techniques, aiming to attain improved engine efficiency, while meeting tail-pipe emission standards. Relative merits, demerits and challenges associated with these combustion techniques are discussed below.

Modern SI engines mostly apply two injection strategies: *Port Fuel Injection* (PFI) and *Gasoline Direct Injection* (GDI) techniques. In PFI system, fuel is injected in the intake port before the intake valve. It leads to fuel metering error, wall wetting, timing lag in fuel delivery, and high unburned hydrocarbon emissions. Direct injection of gasoline inside the combustion chamber can overcome most problems associated with PFI engines, and termed it as gasoline direct injection (GDI) engines. High FIP in GDI engines provides better fuel atomization and lower tailpipe emissions with improved fuel economy (Nohira and Ito 1997; Rottenkolber et al. 2002). However, there are some issues associated with GDI techniques such as high NOx and PM emissions, difficulty in controlling stratified combustion, and high unburned HC and CO emissions at low load (Chincholkar and Suryawanshi 2016).

Low-Temperature Combustion (LTC) technique exhibits relatively lower adiabatic flame temperature than conventional combustion techniques, resulting in lower NOx and PM emissions, while maintaining diesel like high efficiencies. Different LTC techniques are homogenous charge compression ignition (HCCI), reactivity controlled compression ignition (RCCI), and partially premixed charge compression ignition (PCCI). All LTC techniques provide flameless, homogenous combustion of premixed fuel-air mixture ensuring very low NOx formation due to lower adiabatic temperature, and negligible soot formation due to the absence of a fuel-rich zone in the combustion chamber. However, LTC produces higher CO and HC tail-pipe emissions due to reduction in the exhaust gas temperature (EGT) therefore exhaust gas after-treatment devices are essential for controlling CO and HC emissions.

In HCCI engines, fully premixed fuel-air mixture is compressed, and in-cylinder chemical kinetics controls ignition via combustion chamber pressure and temperature. Premixed charge reduces the combustion temperature and local equivalence ratio. Shorter combustion duration leads to a reduction in the heat transfer losses with improved engine efficiency. However high rate of pressure rise (RoPR) and limiting operation under high load range are the main issues encountered in the HCCI engines, which can be manipulated by using combustion phasing.

In RCCI engines, fuels having high auto-ignition temperature such as gasoline, methanol, and ethanol are injected into the port and high reactivity fuels such as diesel or biodiesel is directly injected into the combustion chamber as usual. Best alternative for port injection in RCCI engines is a mixture of alcohols and gasoline. The proportion of each of these two fuels depends on the engine operating condition and other engine parameters. However, only ~10% diesel of total fuel mass is injected into the cylinder to trigger RCCI combustion under most operating conditions. RCCI combustion is capable of achieving near-zero NOx and PM emissions along with high engine efficiency. However requirement of two fuel injection systems increases the cost and complexity of the vehicle significantly.

Premixed Charge Compression Ignition (PCCI) engine (Kimura et al. 1999; Fuerhapter et al. 2003; Cao et al. 2009; Parks II et al. 2010) provides more stable combustion compared to the HCCI engine. It offers more time for mixture preparation before SoC compared to conventional diesel combustion. Ignition of partially premixed fuel-air charge is similar to that of HCCI combustion. Majority of fuel is burned in the premixed phase in PCCI combustion like HCCI combustion, which reduces NOx and PM emissions simultaneously. Similar to other LTC techniques, PCCI combustion faces the same challenges of higher CO and HC emissions compared to diesel engines. However, these CO and HC emissions in PCCI combustion are lower than the HCCI combustion.

5.5 Gasoline Compression Ignition Engine Technology

Gasoline Compression Ignition (GCI) is an advanced engine technology, utilizing low-octane gasoline in place of diesel in CI engines. Gasoline is more volatile with high resistant to auto-ignition, which facilitates homogenous mixing of fuel-air before SoC compared to diesel operation. GCI technology combines the benefits of higher compression ratio (CR) operation of CI engines and positive features of gasoline. It is expected that this new engine-fuel system will be cost-effective because of use of low-octane gasoline, which would be cheaper, and can help reduce exhaust emissions such as NOx and PM simaltaneously. Scope of utilizing a higher percentage of exhaust gas recirculation (EGR) exists, which can further help reduce PM and NOx emissions. Mazda recently launched a new car SkyAktiv X, operating on GCI technology (Mazda 2017).

5.5.1 Principle of GCI Combustion

Gasoline compression ignition (GCI) is an advanced LTC technique that can address the problems associated with diesel engines. GCI engine operates on fully pre-mixed homogenous combustion mode (like HCCI) at low load, on partially pre-mixed combustion (PPC) mode at medium load, and on diffusion-controlled combustion (like a diesel engine) mode at high load condition. Based on the level of mixture homogeneity, partially pre-mixed combustion (PPC) lies in-between the HCCI and CI combustion modes. In PPC mode, fuel-air mixture is burned in combination of both diffusion and pre-mixed mechanisms with bulk auto-ignition. At low loads, fuel is injected in the intake stroke or at the start of compression stroke so that more mixture homogeneity can be achieved whereas at high loads, gasoline is directly injected like diesel near the top dead center (TDC) in the combustion chamber. In GCI engine, level of fuel stratification needs to be improved with increasing engine load, since the ignition delay decreases with increasing load. Therefore, a small amount of combustion takes place by auto-ignition, and the remaining majority of fuel combustion dominated by diffusion process.

5.5.2 GCI Engine Fuel Refining Process

GCI engines can operate efficiently on the low octane gasoline like fuels such as naphtha. Previous studies (Hildingsson et al. 2009) on a single cylinder engine with a compression ratio 16:1 showed that the optimum research octane number (RON) for GCI combustion lies between 75 and 85. Another experimental investigation on a heavy-duty CI engine suggested that optimum RON for GCI combustion should be in the 70’s range (Manente et al. 2011). Optimum fuel properties for GCI engines are listed in Table 5.3 (Kalghatgi et al. 2016).

Mixture of diesel and gasoline or low octane gasoline can extend GCI operating range with enhanced fuel stratification (Won et al. 2012a). Gasoline and diesel blend can easily match the required GCI fuel properties although safety and flash point demand of fuel can be an issue. By only adding >25% components from diesel boiling range in the gasoline/diesel blends, GCI fuel can easily meet safety requirement (Algunaibet et al. 2016; Al-Abdullah et al. 2015). Low octane gasoline has a higher hydrogen/carbon ratio and more paraffinic components. Distillation range of GCI fuel is closer to gasoline than diesel, and new fuel has a higher final boiling point

Table 5.3 Optimum fuel properties for a GCI engine (Kalghatgi et al. 2016)

Properties	Optimum value
Research octane number (RON)	70–85
Cetane number	<27
Density @ 15 °C, kg/m^3	720–800
Initial Boiling Point, (IBP) °C	28
Final Boiling Point, (FBP) °C	250
Olefins, lv%	<18
Aromatics, lv%	<35
Sulfur, wt ppm	<10
Benzene, vol. %	<1

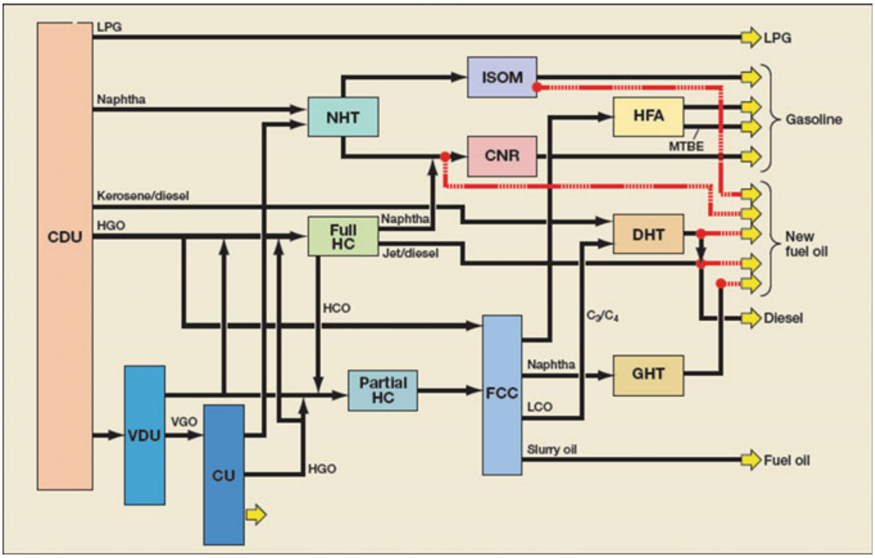


Fig. 5.7 Refinery configuration for new GCI fuel (Kalghatgi et al. 2016) (CDU—crude distillation unit, VDU—vacuum distillation unit, CU—coking unit, HC—hydrocracking unit, DHT—distillate hydrotreating unit, FCC—fluid catalytic cracking unit, HFA—HF alkylation unit, GHT—gasoline hydrotreating unit, NHT—naphtha hydrotreating unit, ISOM—isomerization unit, and CNR—continuous naphtha reforming unit)

compared to baseline gasoline. Refinery configuration for the GCI fuel is almost similar to traditional one except different unit capabilities. Refinery configuration for new GCI fuel is shown in Fig. 5.7 (Kalghatgi et al. 2016).

GHG emissions in refining process for low octane gasoline (12.8 g CO_2-eq/MJ) are lower than that of gasoline (14.8 g CO_2-eq/MJ) and diesel (13.5 g CO_2-eq/MJ) production. Well-to-wheel GHG emissions from a GCI engine is 22% less than an equivalent SI engine and ~9% lower than an equivalent diesel engine. Experimental results of Lu Z. et al. (Lu et al. 2016) suggested that a GCI engine operating on low octane gasoline has 125% higher fuel economy compared to SI engine operating on US gasoline.

5.5.3 *GCI Combustion Modes*

Depending on engine operating conditions, the level of fuel stratification significantly affects the auto-ignitability, combustion phasing, combustion stability, and emissions in a GCI engine. Fuel stratification can be controlled by using the fuel injection strategy. Due to this, GCI is a more practical technique compared to HCCI and can be utilized in commercial diesel engines for a wider operating range with better-combustion stability (Manente et al. 2011; Dec et al. 2011, 2015; Hao et al.

2016; Borgqvist et al. 2012). GCI combustion modes are classified into three categories according to the level of fuel stratification: partial fuel stratification (PFS), medium fuel stratification (MFS), and high fuel stratification (HFS). Multiple injection strategy is utilized in GCI engines for achieving stable combustion and level of fuel stratification, which is determined by using the injection centroid formula (Dempsey et al. 2016):

$$\theta_{inj} = \frac{\sum_{i=1}^{N_{inj}} Y_i SOI_i}{\sum_{i=1}^{N_{inj}} Y_i} = \sum_{i=1}^{N_{inj}} Y_i SOI_i$$

where N_{inj} = Number of injections, Y_i is the fraction of fuel mass in *i*th injection, and SOI_i is the start of injection of *i*th injection.

PFS is used for preparation of homogeneous charge at part-load conditions, in which the first injection takes place either into the port or direct injection in the intake stroke. Main injection takes place in the compression stroke to create desired level of fuel stratification and to auto-ignite the charge so that the engine can achieve low emissions with an acceptable combustion noise. In MFS, level of premixed charge slightly decreases with a slight increase in the fuel stratification level. All injections in MFS mode take place during the compression stroke, in which final injection takes place near TDC to trigger the premixed charge. High level of fuel stratification, with no or very less premixed charge is utilized in the GCI engine at high load condition. In HFS mode, all injection events take place near TDC in the compression stroke (Dempsey et al. 2016). FIP varies to achieve the desired level of fuel stratification in GCI combustion. Higher FIP is utilized in case of HFS compared to MFS and PFS to complete the injection before the SoC. However FIP requirement of HFS is still significantly lower than diesel PCCI due to high self-ignition temperature and high volatility of gasoline. GCI combustion requires lower fuel stratification for the operation with a high level of EGR (Dempsey et al. 2016; Noehre et al. 2006). Effect of different parameters on GCI combustion modes such as PFS, MFS, and HFS are discussed briefly in Table 5.4 (Dempsey et al. 2016). And comparison of various conventional and advanced engine combustion techniques based on the level of fuel stratification before the SoC is captured in Fig. 5.8 (Singh and Agarwal 2019).

5.5.4 GCI Versus Other Combustion Concepts

Implementation of efficient and eco-friendly combustion techniques is the focus of engine researchers at present. Due to increased concerns about emissions and fuel economy, researchers have started to work on alternative combustion technologies such as low temperature combustion (HCCI, PCCI, and RCCI), GDI, and GCI. Comparative analysis of the GCI engine technology with other combustion technologies is discussed in Table 5.5.

Table 5.4 Effects of fuel stratification levels on GCI engine performance, combustion and emissions Parameters (Dempsey et al. 2016)

Parameters	Partial fuel stratification	Medium fuel stratification	High fuel stratification
Injection Period	First injection either in the port or very early in the intake stroke and main injection in the mid-compression stroke θ_{inj}: 320–120°bTDC	All Direct Injection (DI) events take place during compression stroke and main injection near the TDC θ_{inj}: 120°–140°bTDC	Multiple DI events take place near the TDC θ_{inj}: 40°–0°bTDC
FIP	Low	Medium	High, but less than diesel PCCI
Premixing level	Highly premixed before SOC	Medium	No or very less premixed fuel
Combustion and its control	Similar to HCCI combustion with same opportunities and challenges and kinetically controlled combustion identical to HCCI	More closer to diesel PCCI with advanced injection and longer ignition delay, injection driven concept and combustion control mainly by injection near the TDC	Combustion identical to diesel PCCI and injection-induced concept, combustion managed like CDC and diesel PCCI
Opportunities	Ultra-low NOx and soot emissions	Lowest combustion noise and RoPR among all GCI strategies	High combustion efficiency similar to CDC. Low soot emissions
Challenge	Low combustion efficiency, high combustion noise, limited operating range, little control over combustion phasing	Modest combustion efficiency, NOx and soot emissions	High NOx emissions, But lower than diesel PCCI. High RoPR and high combustion noise

5.5.5 Opportunities and Challenges Associated with GCI

High volatility and long ignition delay period of gasoline facilitates superior mixture homogeneity, which eventually allows the GCI engine to operate at lower FIP. Hence, GCI vehicles can be equipped with low-pressure fuel pump, leading to significantly lower cost and complexity of the fuel injection system. Lower FIP improves the GCI combustion stability at part loads and helps in reducing CO and HC emissions as well. By controlling the fuel stratification level, fuel over-mixing and over-leaning of the mixture can be avoided in GCI engine (Kalghatgi and Johansson 2018). GCI technique helps in mitigating the pumping losses and it could be operated at wide-open

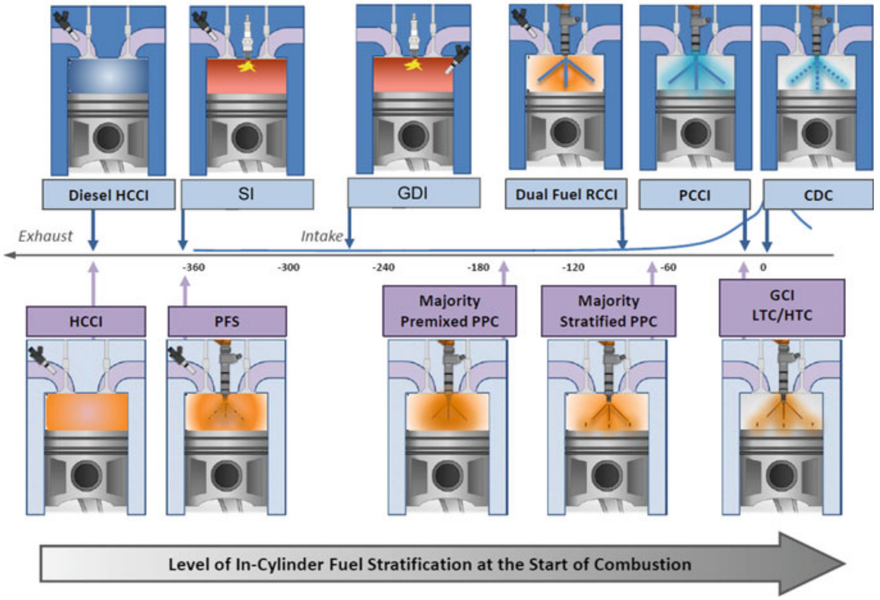


Fig. 5.8 Comparison of various conventional and advanced engine combustion techniques based on the level of fuel stratification before the SoC (Singh and Agarwal 2019)

throttle (WOT) condition at higher compression ratio thus engine can achieve higher efficiency quite similar to conventional diesel engines. Pilot injection is employed in diesel engine at low load condition to reduce combustion noise, but it lowers the engine efficiency and increases the smoke level. This problem can be tackled by GCI fuel, which provides longer ignition delay. Reduced parasitic losses due to lower FIP and less frequently regeneration of particulate filter helps in engine efficiency improvement. However, it is necessary to control high HC and CO emissions of GCI engine by using exhaust gas after-treatment devices. The focus of exhaust gas after-treatment shifts to oxidation of HC and CO in GCI engines, which is much easier and cost-effective compared to controlling NOx and PM emissions in case of a diesel engine. In GCI engines, soot emission increase with increasing engine load. However, its level is always less than that of diesel engine with the same fuel injection system because mixture homogeneity is far better in the previous case. Heavy-duty GCI engine requires a gasoline particulate filter (GPF) to control the soot emissions at high engine load conditions. At high load condition, GPF self-regenerates due to high exhaust gas temperature.

Though a GCI engine produces low NOx emissions, it would require NOx after-treatment device in order to comply with stringent emission norms, however it will be less loaded compared to a DPF. There is scope for developing cost-effective and straightforward after-treatment systems for GCI engines compared to modern diesel engines. Besides, it is necessary to develop oxidation catalysts and GPF that could work at low exhaust temperatures. Figure 5.9 shows that GCI engine technology

Table 5.5 Comparative analysis of different IC engine combustion technologies

Basic Parameters	Conventional Techniques		Low Temperature Combustion			GCI
	SI	CI	HCCI	PCCI	RCCI	
Fuel	Gasoline like fuels	Diesel like fuels	Flexible fuel	Flexible fuel	Combination of fuels	Low octane gasoline
Fuel ignition characteristics	High resistance to auto-ignition (high Octane)	Easy auto-ignition (high Cetane)	Depends upon compression ratio (CR)	Depends upon compression ratio (CR)	High octane fuel in the port and high Cetane fuel via DI	Octane rating in the range of 70–85 (Optimum RON ~70)
Ignition Source	Spark ignition	Auto-ignition	Auto-ignition	Ignited by the main injection	Ignited by the direct injection	Triggered by the main injection
Fuel Injection	PFI/GDI	Direct injection	PFI/DI	Multiple DI	Both Port and DI	Multiple DI
Combustion characteristics and Flame front	Premixed combustion with turbulent flame (homogenous/stratified)	Diffusion combustion without flame (heterogeneous)	Premixed combustion governed by in-cylinder pressure and temp.	Premixed and homogenous combustion without flame front	Premixed combustion controlled by chemical kinetics	Premixed combustion depending upon fuel stratification
Fuel-air ratio	Stoichiometric ($\lambda = 1$), load independent	$\lambda = 1.2–2.2$ linearly dependant on engine load	Lean ($\lambda > 1$)	Lean ($\lambda > 1$)	Lean/stoichiometric ($\lambda > 1, = 1$)	Lean ($\lambda > 1$)
Throttling	Throttled/Unthrottled	Unthrottled	Unthrottled	Unthrottled	Unthrottled	Unthrottled
Ignition control	Spark timing	Injection timing	Kinetically controlled	Injection timing and in-cylinder condition	Main injection timing	By Main injection timing
Emissions	High CO and HC, and low NOx and PM	High PM and NOx	Low PM and NOx	Low PM and NOx	Low PM and NOx with high CO and HC	Low PM and NOx with high CO and HC
Efficiency	Poor part load Efficiency	High Efficiency	Depends on CR	High Efficiency	High Efficiency	High Efficiency like CDC

(continued)

Table 5.5 (continued)

Basic Parameters	Conventional Techniques		Low Temperature Combustion			GCI
	SI	CI	HCCI	PCCI	RCCI	
Challenges	Low engine efficiency and high throttling losses	High PM and NOx emissions, high vehicle cost due to installation of expensive exhaust after-treatment system and FIE system	Relativity high CO and HC emissions with poor combustion stability	Relativity high CO and HC emissions	Relativity higher CO and HC emission and complicated and expensive due to addition of a PFI system	High CO and HC emissions, high RoPR at medium and high load, poor combustion stability at low loads
Advantages	Very low emissions using a 3-way catalytic converter	High Efficiency	Improved efficiency with low emissions	High efficiency with little PM and NOx emissions	High thermal efficiency with low PM and NOx emissions and better control on combustion stability	High efficiency, small PM, NOx, and GHG emissions, operates on low octane gasoline, low-cost vehicle

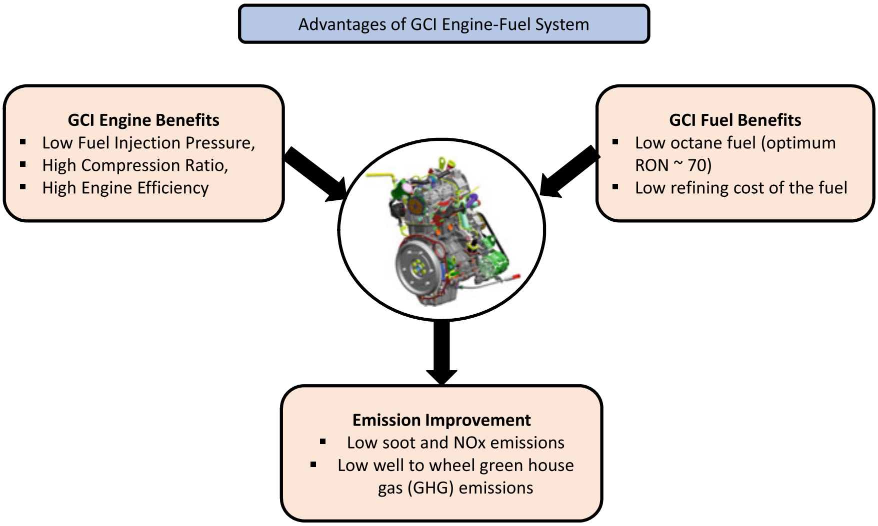


Fig. 5.9 Advantages of GCI engine technology

can reduce vehicle operating cost by using low octane fuel, while maintaining high engine efficiency.

Therefore R&D efforts are required to address the issues associated with GCI engine technology before its adoptation in commercial vehicles. Main challenges associated with GCI technology are captured in Fig. 5.10 (Kalghatgi and Johansson 2018). However, most problems can be resolved by optimizing the combustion. It

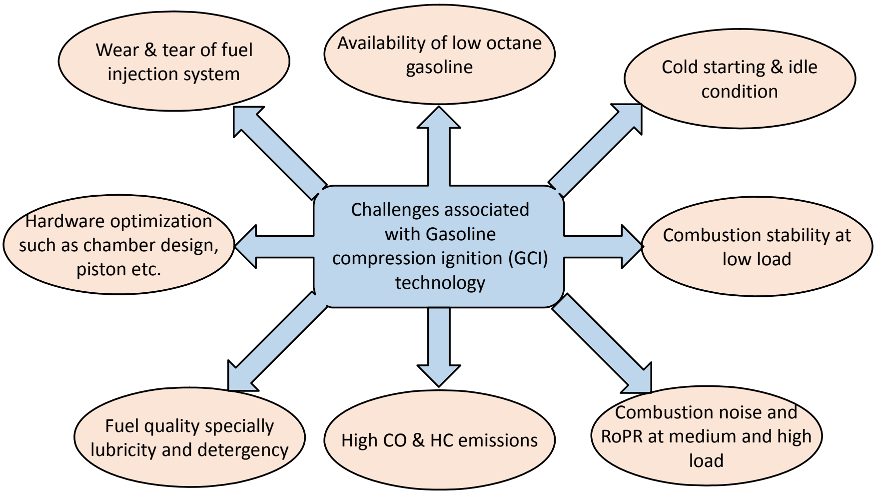


Fig. 5.10 Challenges for GCI engine technology

is much simpler to address the issues associated with GCI engines than the existing diesel engines because diesel engines (CI engines) are the "right engine" operating with the "wrong fuel". Control of PM and NOx emissions from the diesel engine has reached their practical limits. GCI will be an alternative technology to reduce the emissions from CI engines without compromising the engine efficiency. Also it would help in reducing GHG emission footprint (Kalghatgi and Johansson 2018; Mazda 2017). Therefore implementation of GCI technology could be beneficial to both the automotive industry and the oil companies. It opens a path to mitigate imbalance in the future fuel demand for light and heavy fuel oils.

5.6 Effect of Various Control Strategies on GCI Engine

Main issues associated with GCI technique include cold starting problems, high HC and CO emissions, combustion instability at low loads, and high RoPR at medium, and high loads. Like other engine combustion processes, GCI combustion also significantly depends on fuel properties, optimum injection strategies, and engine operating characteristics. GCI technology can be effectively implemented by optimizing injection strategies. Different control strategies that can be employed in GCI combustion towards satisfactory engine performance are described in the following sub-sections.

5.6.1 Injection Strategy

Fuel injection strategies greatly influence engine combustion, performance, and tailpipe emissions. By utilizing split injection strategies in GCI engine, desired level of combustion noise, and knock resistance can be achieved. Split injections (multi-injections) use two or more-injection pulses to control the rate of pressure rise (RoPR), apparent heat release rate (aHRR), and combustion noise. In multi-injection technology, first injection pulse controls the level of premixed charge (mixture homogeneity), and second injection pulse controls the combustion phasing (ignition timing). The effect of pilot injection quantity and fuel quality on mixture condition is shown in Fig. 5.11 (Goyal et al. 2019).

Pilot injection timing and quantity affects the level of fuel stratification and prepares a thermodynamic state for auto-ignition of fuel injected in main injection. It also helps in controlling heat release rate and engine out-emissions (Lu et al. 2011). An optimized injection strategy can help achieve greater productive control on GCI combustion and stretched heat release profile for full engine operating range (Kalghatgi et al. 2007; Sellnau et al. 2012; Manente et al. 2009; Ra et al. 2011; Goyal et al. 2017). Due to long ignition delay of gasoline, injection process and combustion event cannot be easily separated at full load. Extended injection duration and ignition delay result in substantial soot emissions due to diffusion combustion domination at high load (Manente et al. 2010; Lewander et al. 2011). By using multiple injection

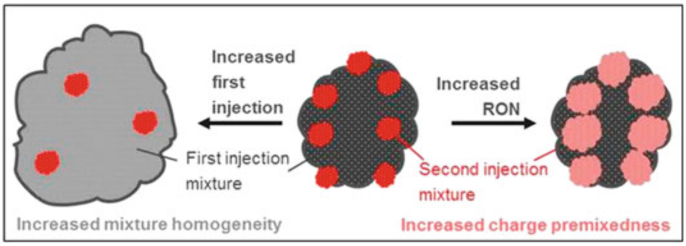
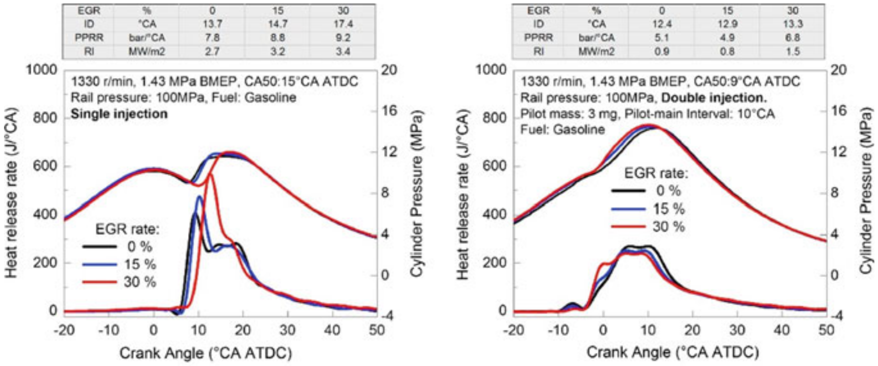


Fig. 5.11 Effect of pilot injection quantity and fuel quality on mixture quality (Goyal et al. 2019)


EGR	%	0	15	30
ID	°CA	13.7	14.7	17.4
PPRR	bar/°CA	7.8	8.8	9.2
RI	MW/m2	2.7	3.2	3.4

EGR	%	0	15	30
ID	°CA	12.4	12.9	13.3
PPRR	bar/°CA	5.1	4.9	6.8
RI	MW/m2	0.9	0.8	1.5

(a) Single injection

(b) Double injection

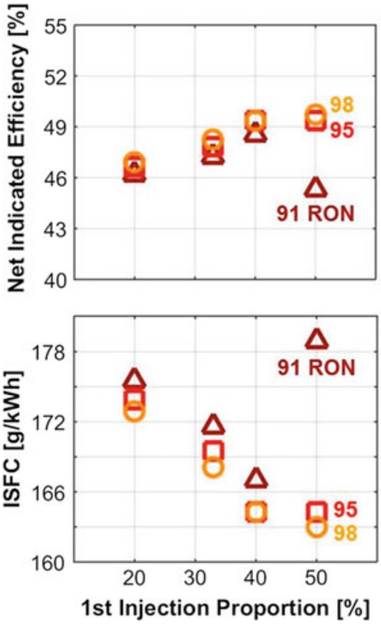
Fig. 5.12 In-cylinder pressure and HRR of GCI combustion engine under **a** single injection and **b** double injection (Mao et al. 2018)

strategy, lower PM and NOx emissions from a GCI engine can be achieved due to improved charge homogeneity, similar to HCCI engines (Kalghatgi et al. 2007; Ra et al. 2012; Zhao et al. 2003; Gray III and Ryan III 1997; Thring 1989), while oxidation of unburned species can lower HC and CO emissions at high temperature due to superior premixing of charge.

Mao et al. (2018) optimized injection strategies of a GCI engine and suggested that a single injection strategy could not be employed effectively in GCI combustion engine due to knocking and substantial reduction in fuel economy (Fig. 5.12). Pilot injection reduced the ignition delay, improved combustion noise and controllability, and reduced the emissions. They achieved a peak brake thermal efficiency (BTE) of ~44% at 1350 rpm in a multi-cylinder GCI engine with Euro-VI NOx emissions.

Goyal et al. (2019) investigated the effect of pilot injection quantity and fuel quality (RON 91, 95 and 98) on a single-cylinder GCI engine operating at 2000 rpm at 940 kPa IMEP. They reported that at fixed RON, an increased proportion of pilot fuel quantity leads to an improvement in mixture homogeneity and slows down initial burning rate, as shown in Fig. 5.13.

Fig. 5.13 Indicated thermal efficiency (ITE) at different pilot/first injection proportion and fuel ignition quality at fixed combustion phasing (CA50 at 10°CA aTDC) (Goyal et al. 2019)



Increased pilot injection quantity provided stretched heat release profile with lower combustion noise. Results suggested that 50% first injection proportion with 91 RON achieved the lowest combustion noise and peak pressure rise rate (PPRR). Enhanced mixture homogeneity reduced the in-cylinder reaction temperature resulting in NOx reductions. However, a more moderate reaction temperature can reduce the oxidation rate, which results in increased emissions of CO, HC, and smoke. Researchers obtained an indicated thermal efficiency (ITE) ranging from 45 to 50% in the GCI engines (Fig. 5.13). Even the lowest efficiency (41%) of GCI engine was relatively higher than the reference diesel engine efficiency.

5.6.2 Fuel Ignition Quality

Gasoline has a lower cetane number (usually <15) which provides longer ignition delay before SoC. It should be injected earlier in the compression stroke at lower in-cylinder pressure and temperature conditions, which are not favorable for auto-ignition of gasoline. Utilization of EGR in GCI combustion further retards the ignition reactions (Cracknell et al. 2008). Ignition delay model was developed for diesel combustion in warmed-up engine conditions (Vallinayagam et al. 2018), and it was extended to estimate ignition delay at lower temperatures or for the fuels having different Cetane ratings. Results showed that ignition delay increased by three times,

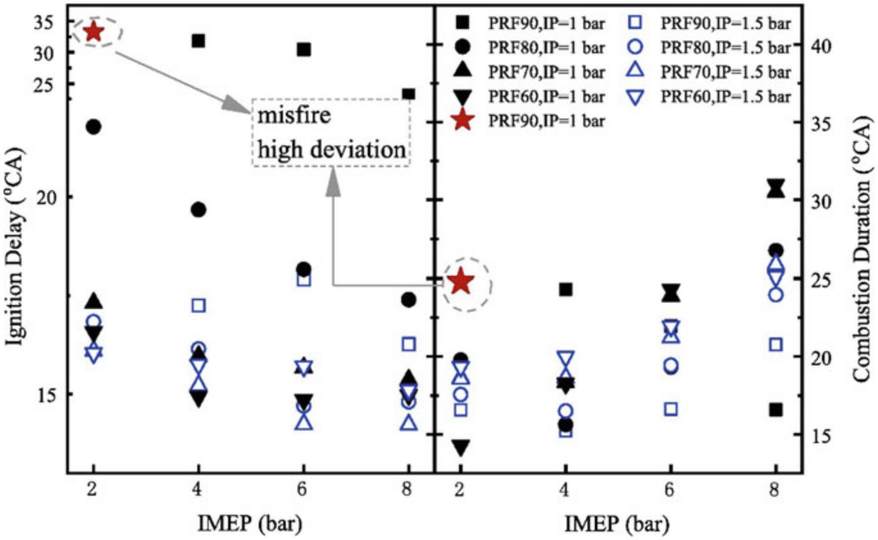


Fig. 5.14 Effect of intake air pressure (IP) on the ignition delay and combustion duration at different engine load conditions (Jiang et al. 2019)

when the engine coolant temperature dropped from 100 to 0°C and was doubled for gasoline (CN15) as compared to baseline diesel.

Jiang et al. (2019) investigated the performance and emissions characteristics of GCI engine fueled with four different primary reference fuels (PRFs) having research octane number of 60, 70, 80, and 90. Figure 5.14 (Jiang et al. 2019) shows the effects on intake air pressure (IP) on combustion duration and ignition delay. Results showed that combustion was unstable with PRF90 at 2 bar IMEP because of longer ignition delay period. Researchers suggested that GCI engine delivered better performance and engine efficiency using PRF70 with intake air heating at part load (IMEP between 1 and 4 bar). PRF70 provided good results at medium loads (IMEP between 4 and 8 bars) and PRF90 above IMEP of 8 bar without intake air heating. Up to 47% ITE with PRF70 under medium load was observed in this study.

Cho et al. (2017) et al. conducted experiments with the US market gasoline (RON92 E10) and RON80 gasoline on Delphi's 2nd generation GCI engine at different load conditions. GCI engine utilized a high amount of EGR (~44%) with RON80 compared to conventional gasoline (EGR ~39%) for the same combustion phasing at lower temperature and pressure. Due to difference in fuel reactivity, they achieved 10.9% lower BSFC, and improved combustion stability (COV 0.50% for RON80 and 0.99% for conventional gasoline) at part and medium loads. Overall, RON80 was better in terms of efficiency, stability, and emissions compared to RON92 E10 gasoline.

Goyal et al. (2019) reported that higher RON fuels and fixed pilot injection quantity leads to higher premixing of fuel injected during main injection event, which increases combustion noise and peak aHRR. Researchers added that engine efficiency

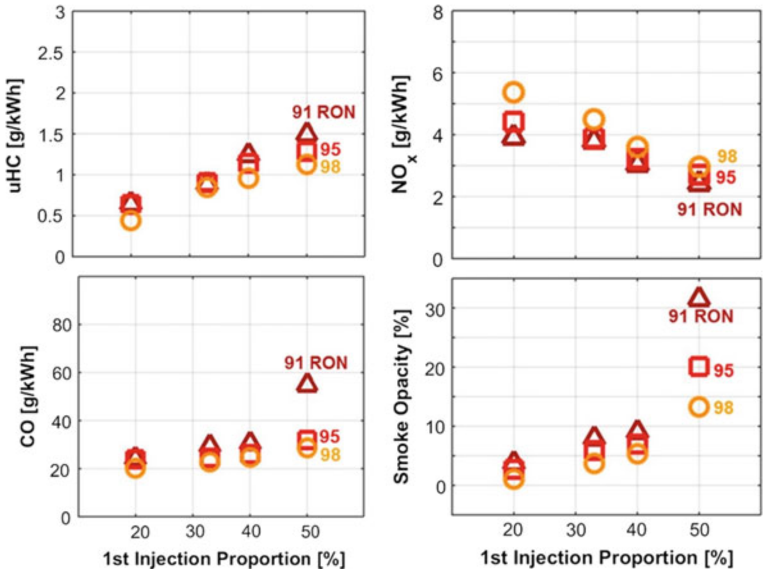


Fig. 5.15 Engine out NOx/HC/CO and smoke emissions at different pilot injection proportions and fuel ignition quality at fixed combustion phasing (CA50 at 10°CA aTDC) (Goyal et al. 2019)

improved with increasing RON of the test fuel but decreased with increasing first injection quantity. However higher RON with fixed mixture homogeneity resulted in over-premixing of the second injection. It increased engine-out NOx emissions due to high reaction temperatures but it reduced the engine-out HC, CO and smoke emissions. Effect of pilot mass and fuel ignition quality is shown in Fig. 5.15 (Goyal et al. 2019) with fixed combustion phasing.

5.6.3 *EGR Strategy*

Effective control of used EGR reduces NOx emissions by controlling the in-cylinder temperature and oxygen level. Ra et al. (2011) investigated the effect of EGR, injection timing, and fuel split ratio on a light-duty diesel engine in GCI mode at full load (16 bar IMEP, 2500 rpm). They obtained lower PM and NOx emissions (0.1 g/kg-f) and low ISFC (180 g/kWh) due to lower combustion temperature by utilizing high EGR, high volatility and high octane rating of gasoline. Decreasing EGR ratio helped in retarding injection timing for optimum GCI combustion. Similarly Kolodziej et al. (2016) suggested that increased fuel reactivity (lower octane rating) required more EGR for controlled GCI combustion. Yao et al. (2015) reported that lower octane gasoline improved the NOx-PM tradeoff with a high level of EGR. They utilized multiple injection strategy with 50% EGR and demonstrated an ITE of 51.57% with lower maximum RoPR and regulated emissions.

5.6.4 Other Control Techniques

5.6.4.1 Negative Valve Overlapping

Higher RON gasoline has longer ignition delay that creates a problem in combustion at low loads in GCI engine. This can be resolved by a strategy called negative valve overlapping (NVO), i.e. closing the exhaust valve very early in the cycle. Vallinayagam et al. (2018) extended idle and low load stability of GCI combustion using NVO strategy. They varied the exhaust cam phasing so that exhaust valve closes very early. Recompression of hot gases took place before opening of intake valves, which helped in auto-ignition of charge and improved the combustion stability at low loads. With NVO, intake air temperature requirement decreased by 15–20 °C. NVO reduced engine efficiency at low loads due to more heat losses, but it helped in reduction of CO and HC emissions.

5.6.4.2 Controlling Intake Temperature and Pressure

Jiang et al. (2019) investigated the effect of intake temperature and pressure on the GCI engine combustion and emissions. Increasing intake pressure to 8 bar enhanced GCI engine fuel economy by 20 g/kWh at low RON of 70. They reported that increasing intake pressure advanced the combustion and the combustion phasing. Supercharging helped reduce HC and CO emissions due to proper burning and led to a reduction in NOx emissions. However total PM increased at part load conditions. Increasing intake temperature decreased engine's volumetric efficiency, and HC and CO emissions at part load but increased NOx emissions due to relatively higher peak in-cylinder temperature. ITE improved by 16% using PRF70 at intake temperature of 50 °C compared to PRF90 at 30 °C.

5.6.4.3 Effect of Ozone Seeding on GCI Engine

Seeding ozone in intake air improves gasoline reactivity thus can enhance the low load limit of a GCI engine as reported by Pinazzi and Foucher (2017). Ozone seeding reduces the intake air temperature, and subsequently lowered the combustion temperature, resulting in reduction of NOx emissions. Researchers suggested that first injection should be in intake stroke so that ozone get more residence time, and second injection should be in compression stroke to control the level of fuel stratification, avoiding excessive heat release rate. However overall combustion and indicated efficiency can be affected because of large time gap in the injection events.

5.7 Critical Parts of a GCI Engine

GCI technique can be adopted in modern CI engines with minimal modifications in engine design and fuel injection system. It requires a simple fuel injection system and exhaust after-treatment system that can reduce vehicle cost and complexity. In this section, adoption of GCI technique in the contemporary CI engines is summarized.

5.7.1 Fuel Injection System

Fuel injection system is a critical part of a CI engine that affects engine performance, combustion, and tail-pipe emissions. High FIP is required for adequate atomization and mixing of the charge. As the FIP increases, cost, and complexity of the system increases simultaneously. In case of GCI engine, FIP depends on the operating condition and desired level of fuel stratification. Even with high volatility of gasoline, FIP can go up to 1000 bar at full capacity of a GCI engine. CRDI fuel injection system would be a better choice for GCI engine with minor modifications in fuel injector geometry. Fuel injector design should be such that it can provide sufficient fuel quantity at desired FIP. Lower FIP helps reduce power requirement for the fuel pump. For example, reducing FIP from 1460 bar to 960 bar reduces fuel pump power by about 100 W. GCI engines can operate at half of diesel engine's FIP. A GCI engine can achieve the lowest BSFC in between 80 and 110 MPa injection pressure. Gasoline has lower density and calorific value (by volume) compared to diesel, hence more quantity is required to be injected to achieve diesel-like power output. Therefore gasoline fuel injector holes for a GCI engine would be slightly larger than the diesel injector holes. Otherwise, fuel injection period needs to be increased, if a diesel injector is to be used to inject gasoline in a GCI engine.

Lubricity of market gasoline is not adequate to protect the fuel injection system from wear and tear. Hence it requires either a careful selection of material for the fuel injection system or addition of suitable additives in gasoline for improving its lubricity (Rose et al. 2013). Won et al. (2012) suggested that large injector hole and lower FIP could be beneficial for GCI combustion. In contrast to these results, Rose et al. (2013) reported that a smaller injector diameter performs better at full operating range of the engine. With a fixed nozzle size, it is better to utilize multiple fuel injections at low FIP in GCI combustion in order to control the combustion noise.

5.7.2 Compression Ratio

Compression ratio (CR) dramatically changes the ignition delay period. Previous studies (Stone 2012; Al-Abdullah et al. 2015; Ra et al. 2011) confirmed that GCI engines can work efficiently using similar compression ratios, ranging from 16.5 to 19, as that of conventional diesel engines. Rose et al. (2013) investigated the effect of two different compression ratios (CR17 and CR19) in a GCI engine. Higher CR (19:1) provided shorter ignition delay period, allowing better control on GCI combustion at low engine loads. At full capacity, CR19 provided better efficiency due to reduced losses. However, use of higher CR was limited by smoke emission, noise, and exhaust gas temperature. Researchers concluded that utilization of variable compression ratio (VCR) could be beneficial for GCI engines. However, another study showed that lowering CR of heavy-duty Cummins engine from 18.9 to 15.7 improved soot-NOx tradeoff at the expense of engine efficiency (Won et al. 2012b), without altering the bowl geometry.

5.7.3 Engine Management System

Optimum performance of an engine depends on different operating parameters such as FIP, injection timing, injection quantity, intake air conditions, and EGR. These parameters must be controlled simultaneously in order to achieve optimum engine performance at given operating conditions. Automobile companies use a preset non-programmable electronic control unit (closed ECU) in vehicle for attaining optimum performance of the engine. As mentioned previously, GCI engines would require multiple injections strategy for achieving better combustion stability and engine performance. Therefore, an open ECU (programmable ECU) has to be used instead of a closed ECU to control and optimize different influencing parameters mentioned earlier. Different sensors and actuators such as lambda sensor, cam sensor, crank sensor, and various temperature and pressure sensors are usually connected to an open ECU and a user can reprogram the ECU as per requirement. Thus an optimized engine management system can effectively and efficiently control in-cylinder conditions by varying the EGR rate, boost level, and valve timing (Fig. 5.16).

5.7.4 GCI Exhaust After-Treatment System

GCI engine emits lower tailpipe NOx and PM emissions but higher HC and CO emissions than diesel engine. Fortunately, it is much simpler to control NOx and PM emissions in GCI engines (Rose et al. 2013). However, GCI will require efficient oxidation catalyst to control the HC and CO emissions at low exhaust gas temperature and gasoline particulate filter (GPF) in order to comply with emission regulations. Regeneration interval of GPF in GCI vehicles will increase and save ~1.5% fuel compared to diesel DPF equipped vehicles.

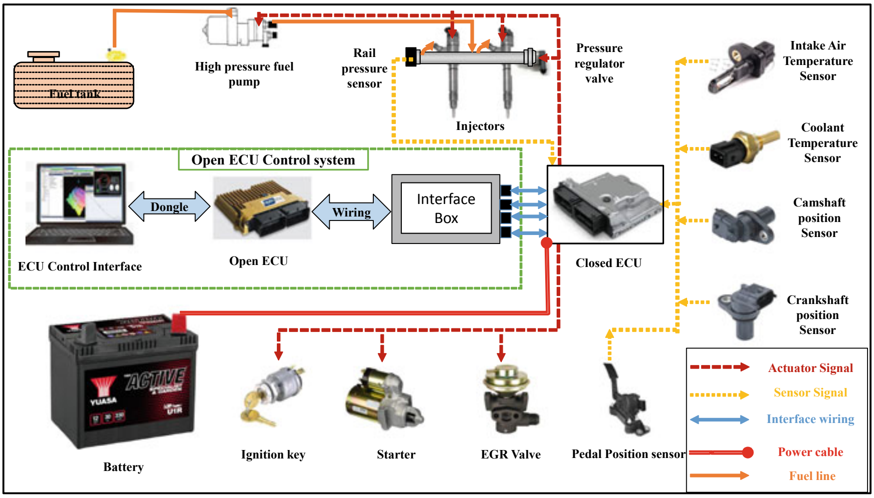


Fig. 5.16 Open ECU interface and engine management system

5.8 Path Forward for GCI Engine Technology

Gasoline compression ignition (GCI) offers an efficient and eco-friendly combustion technique at a reasonable cost. GCI engine can operate efficiently with low octane fuels (RON 70) in the diesel boiling range. Straight run gasoline after the first distillation can be utilized in GCI engines without any post-processing. In initial phase, GCI vehicles can be operated with gasoline-diesel blend in case of unavailability of low octane fuel. However, in order to commercialize GCI vehicles in the current market, significant R&D efforts are needed in the following directions:

(i) GCI engines need to improve combustion stability at part loads. GCI engine fuelled with conventional gasoline has poor combustion stability at low loads due to higher ignition delay, lower cylinder pressure and temperature. Operating parameters such as fuel injection strategy, fuel ignition quality (octane rating), EGR rate, intake pressure and temperature, and piston bowl geometry need to be optimized for effective control of combustion at low loads. Strategies like advanced fuel injection, multiple-injection, low octane fuel usage, negative valve overlap, intake air heating, and EGR usage effectively addresses this issue.

(ii) Combustion control at cold start and idle condition is still an issue with GCI technology. In-cylinder environment at this condition (i.e. low pressure and temperature) is not favorable to auto-ignition of low reactive fuels. To overcome this problem, a suitable combination of fuel ignition quality, advanced injection timing, preheating of intake air, EGR, and NVO can be employed. Glow plug or spark plug can also be used to address the issue of cold start.

(iii) Optimized injection strategies would be needed to control high noise and high rate of pressure rise (RoPR) at medium and high engine loads. Double and triple fuel injections, optimized injection timing and fuel quantity can be beneficial, depending on engine operating conditions.
(iv) GCI engines emit lower NOx and PM emissions but higher HC and CO emissions than a diesel engine. Therefore development of an exhaust gas after-treatment system consisting of efficient oxidation catalysts to control HC and CO emissions at low exhaust gas temperature is essential. Additionally, development of particulate filter will also be required to capture fine soot particles coming out from the engine tailpipe.
(v) Development of close-loop control and sophisticated engine management system can help GCI engine to operate efficienctly in transient operating conditions. Close loop control can help optimize the operating parameters as per driving cycle requirements instantaneously.
(vi) Fuel injector (with optimum hole size and number), fuel pump, piston geometry, and inlet port are some of the crucial parts, that are needed to be designed properly for effective implementation of GCI technique. R&D efforts are needed to develop suitable additives to improve gasoline lubricity without affecting engine tailpipe emissions.
(vii) Availability of low octane fuel in the market is a major concern associated with implementation of GCI fuel-engine system. A blend of iso-octane and n-hexane with suitable additives can be a suitable test fuel for GCI engine.

In addition to the points mentioned above, R&D efforts should be directed towards the reduction of overall system complexity, and costs, while ensuring easy adaptability of GCI technique to existing CI engines.

5.9 Summary

GCI is an advanced engine combustion technology, which improves engine efficiency, while maintaining low levels of tail-pipe NOx and PM emissions. The issues of high PM and soot formation in diesel engines can be minimized by substituting diesel injection quantity by more volatile and medium reactivity fuels such as low octane gasoline. Investigations of microscopic and macroscopic spray characteristics show that gasoline has a lower spray penetration length than diesel under evaporative ambient conditions, which reduce the chances of wall-wetting in GCI engines. GCI engine can therefore operate efficiently with low octane gasoline fuels. Low octane requirement of GCI engine is beneficial since it can reduce well-to-wheel GHG emissions as well as refining costs. GCI engine operates on three levels of fuel stratification such as partial, moderate, and high, which facilitate optimization of vehicle's performance and emissions under variable operating conditions. Opportunities and challenges associated with all combustion modes like PFS, MFS, and HFS have been discussed in detail.

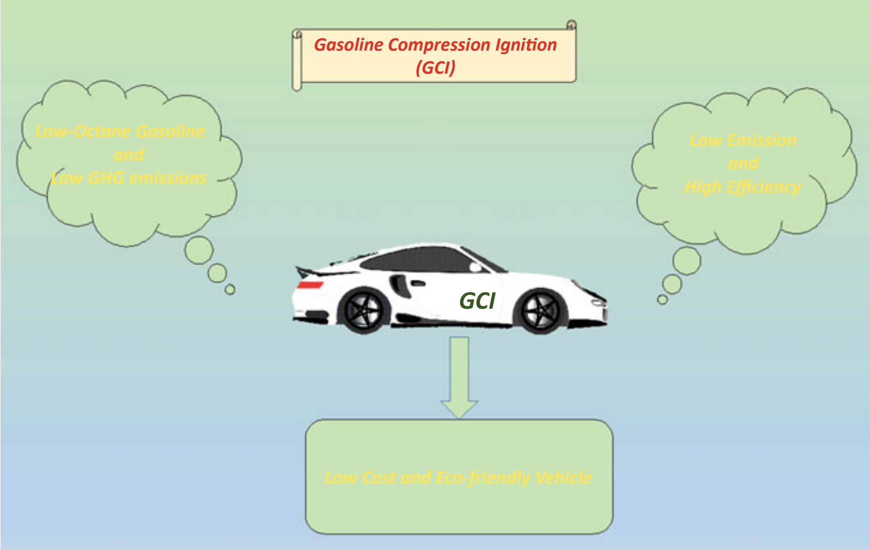


Fig. 5.17 Future of GCI fuel-engine system

Spilt fuel injections strategy can help reduce the combustion noise to a desired level in a GCI engine. Part-load stability of GCI engines can be improved by using NVO, early first injection, EGR and glow-plug. GCI engines would require a robust fuel injection system with a slightly larger injector hole diameter. Maximum compression ratio of a GCI engine depends on operating conditions but is usually between 16:1 to 19:1. Although remarkable progress has been made in the field of GCI technology, high RoHR and combustion noise at medium and full loads, high HC and CO emissions, combustion stability at low loads, cold and idle conditions, and unavailability of low octane fuel are the major obstacles in adoption of GCI technology commercially. Proper optimization of different key influencing parameters discussed in this chapter as well as continuous R&D efforts are quite crucial to address these challenges associated with GCI engines. It can be concluded that it would be easier to work with GCI fuel-engine systems rather than controlling the emissions from diesel engines, hence GCI technology has a bright future in transport sector, as shown in Fig. 5.17.

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