Chapter 2
Combustion-Based Transportation in a Carbon-Constrained World—A Review

Tamour Javed, Ahfaz Ahmed, Vallinayagam Raman, Awad B. S. Alquaity and Bengt Johansson

Abstract The transportation sector accounts for around a quarter of global CO_2 emissions and is powered predominantly by fossil-derived fuels. The regulatory framework is evolving globally to more stringent requirements for fuel efficiency and CO_2 emissions, forcing the OEMs to adopt advanced powertrain technologies. Such changes are more evident in the light-duty road transportation sector compared to the heavy-duty road, marine and air transportation sectors. Here, a holistic review of the current and prospective regulations targeted at curbing transportation-based CO_2 emissions is presented. For road transport, these include various government- and state-level policy initiatives such as the Corporate Average Fuel Economy (CAFE) and CO_2 emission standards and the zero emission mandates. For marine and aviation sectors, these include the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO) regulations and aspirations targeted at reducing the CO_2 footprint. The compliance options for these regulations are evaluated using a combination of fuels, engines, and hybridization in each transportation sector. Furthermore, a brief overview of how OEMs are working toward achieving these targets is presented. An overview of several advanced spark and compression ignition engine technologies with the potential to improve the fuel economy and CO_2 emissions is presented. Finally, an overview of major disruptions that are changing the road-based transportation is presented and a balanced life cycle based policy approach is advocated.

T. Javed (✉)
Fuel Technology Division, Research and Development Center,
Saudi Aramco, Dhahran, Saudi Arabia
e-mail: tamour.javed@aramco.com

A. Ahmed · V. Raman · B. Johansson
Clean Combustion Research Center, King Abdullah University
of Science and Technology, Thuwal, Saudi Arabia

A. B. S. Alquaity
Institute for Combustion Technology, RWTH Aachen University,
52056 Aachen, Germany

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2.1 Introduction

2.1.1 History

Combustion of fuels has been a dominant source of energy for mankind since ages. In primitive times, wood was the major fuel used for heating, lighting, and cooking purposes. As mankind's understanding of their surroundings improved, the focus shifted to an improved version of fuels such as coal, marking the beginnings of the fossil fuel era (Morris 2015). Coal-offered significant advantages over wood such as higher energy density, better flammability, etc., making it a fuel of choice for heating, lighting, and even powering mobility. Locomotives with coal-powered steam engines were introduced in the eighteenth century and became popular (McNeil 2002). Arguably, a paradigm shift in mobility came along when Nikolaus Otto patented his 4-stroke engine in 1876 along with Gottlieb Daimler and Wilhelm Maybach, which used one of the light fractions from crude oil distillation as fuel (Morris 2015). Henry Ford eventually reinforced the significance of this discovery in 1908 when he introduced the first mass-produced affordable vehicle, Model-T. This innovation, along with other similar developments in the European markets, revolutionized the personal mobility sector leading to its wide acceptance among common people. Despite enabling freedom of movement for the mass population, the early vehicles were riddled with issues such as poor fuel efficiency, low power density, and were very high on carbon emissions. These shortcomings became more evident (De Groot 1996; Tushman 1997; Kline and Rosenberg 2009) when the World Wars broke out in Europe and to support the war effort, fuel efficient and high powered vehicles were needed. One inhibitor in improving the fuel efficiency of these engines was their low compression ratio, which was limited by engine knock (Seyferth 2003). Fuels at that time had lower octane numbers because of limited advancement in refinery processes (Splitter et al. 2016) such as catalytic reforming, cracking, etc. Amid attempts on engine and fuel improvement in the 1920s, a young engineer Thomas Midgley and his associates came up with the suggestion of blending small quantities of Tetra Ethyl Lead (TEL) to the gasoline to increase its knock resistance and hence allowing engines to deliver higher power and better efficiency in the process. However, due to health and environmental impacts of TEL, it was phased out in the 1970s around major parts of the world, thereby affecting the automotive efficiency adversely (Splitter et al. 2016). Soon after, automotive manufacturers started using electronic fuel injection system and engine management software, which revived engines' performance to TEL levels.

The foci of the automotive industry till this point were to improve fuel efficiency and power density while the emissions were of little concern.

The obliviousness toward increasing pollutant emissions from vehicles led to the constitution of California Air Resources Board (CARB) in California (United States) in 1967 (Hanemann 2008). This board established regulations on vehicular emissions paving the way for Environmental Protection Agency (EPA) in the US and EU emission standards in the Europe and subsequently around the world. These regulatory bodies acted primarily to address the poor air quality in the developed parts of the world. However, in the same context, another significant event took place in 1966. World Meteorological Organization (WMO) (a body within United Nations) published a report (Mitchell et al. 1966) on climate change which referred to human activity as a predominant reason causing the alteration of natural course of Earth's climate regulating processes. These findings were later followed by the commencement of the United Nations Climate Change Conferences under the United Nations Framework Convention on Climate Change (UNFCC 1992). The main goal of the UNFCC is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

Since then, two meetings of UNFCC have had a significant impact in shaping global climate change policies. In 1997, during Kyoto summit, it was decided that the participating states will strive to reduce greenhouse gas emissions based on the scientific consensus that global warming is occurring and it is extremely likely due to anthropogenic CO_2 emissions. During the second meeting in Paris, an agreement to keep the increase in global average temperature to well below 2 °C above pre-industrial levels was reached (UNFCC 2015); in addition to the consensus to limit the increase to 1.5 °C to substantially mitigate the risks associated with climate change.

2.1.2 Overview

The agreements ratified at these meetings were executed in different versions across major parts of the world with a unified goal to cut down on greenhouse gases promoting climate change. These agreements, however, also led to an increased attention on the emissions from the combustion engines, since automotive sector accounts for around 25% of carbon emissions. To address these implicit demands placed on automotive industries, many new technologies came to forefront including advanced gasoline and diesel technologies. Although these engine technologies are significantly fuel efficient than conventional engines and facilitate tremendous control of emissions with high power density, major economies around the world still felt the need to take more aggressive steps toward curbing the carbon emissions from the vehicular operation. It eventually led to various announcements during 2016–2018 by many countries including the United Kingdom, China, India, parts of Europe etc. to move away from new sales of passenger vehicles powered by pure internal combustion engine in 2030–2040 timeframe. However, the nature of technology to replace internal combustion engines on such a large scale is still under debate. In the most likely scenario, it seems that the combustion engines will stay for longer than hyped in the popular media, especially in the heavy-duty road transport, marine and aviation sectors; however, to address the stricter regulations, combustion engines must reinvent themselves.

In this chapter, first, the regulatory framework around the world and their potential directions in response to climate change, including road transport, marine, and aviation sectors are discussed. In Sects. 2.3 and 2.4, the focus is shifted to fuel and engine technologies in various transportation sectors including their historic trends and current efforts to address the market demands and legislations. Further, a brief review of sustainability efforts by major automakers, in the road transport sector, will be provided. Finally, major trends of disruptions in the transportation sector, using examples of important disruption agents, are discussed. In the end, a holistic overview of the entire chapter is presented.

2.2 The Regulatory Framework

2.2.1 *Fuel Economy and CO_2 Emission Standards for Road Transport*

As a response to climate change, increasing fuel import bills, energy security, and wider impacts of transportation sector on the environment, the regulatory framework across the world to improve the fuel economy and reduce the CO_2 emissions has evolved over the past 50 years and has become quite stringent. Figure 2.1 shows the improvements in CO_2 emissions and fuel economy over the years for passenger cars and light trucks (including pickup trucks, minivans, and SUVs) in the US market. Between 2004 and 2016, the CO_2 emissions and fuel economy have improved by 22 and 28%, respectively (EPA 2017). The benefits of such

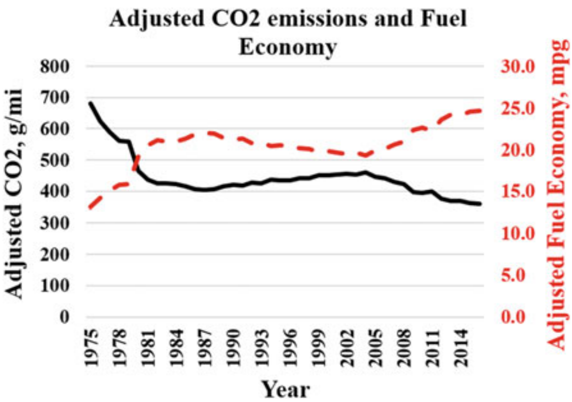

Fig. 2.1 Historic CO_2 emissions reduction and fuel economy improvement in the US for passenger cars and light trucks (EPA 2017)

regulations are further amplified in the passenger cars sector where adjusted fuel economy has reached a historic high of around 29.1 mpg in 2017. Such improvements are consistent in the rest of the world as well and EU reported a CO_2 reduction of 16% in the 2010–2015 period (EU 2018).

As seen in the figure above, the regulatory framework has evolved significantly over the past decade. Just over a decade ago, only the US, Japan, South Korea, and China had enforced regulations for the CO_2 emissions and fuel economy (Yang and Bandivadekar 2017), while the EU and Canada had expressed their aspirations for such regulations. However, in 2017, such regulations are commonplace and enforced in 80% of the light-duty vehicle market. These standards are too detailed to be summarized here, and only a brief overview of these standards is presented. Table 2.1 shows the fuel economy and CO_2 emissions of passenger cars and light trucks in the US (Transport Dept 2012), the EU (Regulation (EU) No 333 2014; Regulation (EU) No 253 2014), China and India (Yang and Bandivadekar 2017). In the US, National Highway Traffic Safety Administration (NHTSA) sets the fleet regulations called the Corporate Average Fuel Economy (CAFE) standards since 1975, and Environmental Protection Agency (EPA) sets the CO_2 standards since 2007, both standards are harmonized since 2010 for the cars and light-duty trucks of the model year 2012 and beyond. The EU legislation sets EU-wide CO_2 emission targets for new cars and commercial vehicles (vans) sold in the EU market. Similar

Table 2.1 Fuel economy and CO_2 emissions of passenger cars and light trucks in the US (Transport Dept 2012), the EU (Regulation (EU) No 333 2014; Regulation (EU) No 253 2014), China (Yang and Bandivadekar 2017) and India (Yang and Bandivadekar 2017)

Country/region	Category	Fuel economy and CO_2 emissions (in year)
US	Cars	36.2 mpg and 225 gCO_2/mi (2016)
		55.3 mpg and 143 gCO_2/mi (2025)
	Light trucks	28.8 mpg and 298 gCO_2/mi (2016)
		39.3 mpg and 204 gCO_2/mi (2025)
EU	Cars	130 gCO_2/km (2015)
		95 gCO_2/km (2021)
		30% CO_2 reduction compared to 2021 (2030)
	Vans	175 gCO_2/km (2017)
		147 gCO_2/km (2020)
		30% CO_2 reduction compared to 2021 (2030)
China	Cars	6.9 L/100 km (2015)
		5 L/100 km (2020)
	Light trucks	6.9 L/100 km (2020)
		–
India	Cars	130 gCO_2/km (2017)
		113 gCO_2/km (2022)
	Light trucks	–
		–

government bodies set the fuel economy and/or CO_2 emissions standards in China, India, and in rest of the world. However, there are some differences in the interpretation of these regulations. First, vehicles are categorized differently in different regions; the maximum Gross Vehicle Weight (GVW) for passenger cars and light-duty trucks in the US is 3856 kg, whereas that in the EU, China, and India is 3500 kg (Yang and Bandivadekar 2017). Also, the test cycles used for reporting and certifying these regulations are different. The US regulators use US combined cycle, while the EU, China, and India use New European Driving Cycle (NEDC). EU plans to shift to a worldwide harmonized Light vehicle Test Procedure (WLTP) in the future (Yang and Bandivadekar 2017). Therefore, direct comparison of these standards across various regions should be reported cautiously. However, across the globe, such standards are becoming ever stringent and the CO_2 emissions in most regions are expected to reduce by around 50% by 2025 compared to baseline years (baseline year is different for different regions, see Table 2.1) (Yang and Bandivadekar 2017). Hence, it could be stated that such regulations are successful in reducing the global warming impact of the transportation sector and also bear financial benefits to the consumers and governments.

The fuel economy and CO_2 emission standards for the Heavy-Duty Vehicles (HDVs) are still evolving compared to Light-Duty Vehicles (LDVs). The EU only recently (COM//284 (EU) 2018) presented proposals for regulating HDV CO_2 emissions. The EU proposals calls for 15 and 30% reduction in CO_2 emissions, compared to 2019 levels, by 2025 and 2030, respectively, whereas 2030 reduction targets are subjected to review in 2022. Moreover, the EU proposals target only large lorries to start with and plan to widen the regulatory coverage to other HDV's post 2022. In 2016, the US EPA and NHTSA jointly announced the fuel economy and CO_2 emissions phase-II standards for medium- and heavy-duty vehicles through the model year 2027 (Transport Dept 2016). These standards are performance-based and are expected to further improve fuel savings by 25% compared to terminal phase-I respective category baseline. They rely on available and futuristic technological improvements to achieve the targets with a neutral attitude toward different technologies. In China, the stage-II and stage-III standards for HDV fuel consumption are expected to improve the fuel economy by 15% compared to 2015 levels by 2021. Fuel consumption standards for HDVs are also planned to be regulated in phases in India starting in 2018 (phase-I effective from 2018, phase-II effective from 2021) (Garg and Sharpe 2017). It is expected that the coverage of fuel economy and CO_2 emissions standards will continue to grow across the world and these standards will continue to evolve towards stricter targets.

2.2.2 *The Zero-Emission Mandates*

Several regulatory bodies, at the country/region and state level, have started enforcing regulations that require automakers to directly invest in zero-emissions vehicles (Battery Electric Vehicles (BEVs), Fuel Cell Vehicles (FCVs)). In 2016, the US state of California issued the Zero-Emissions Vehicle (ZEV) mandate for passenger cars, light-duty trucks, and medium-duty vehicles (CARB 2016). The ZEV mandate since then has been adopted by nine other US states including Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. At the core of this mandate, the automakers are required to produce a certain percentage of their vehicles conforming to ZEV standards. This mandate assigns credit based on the zero emitting drive range, e.g., pure ZEVs, i.e., BEVs and FCVs, depending on their driving range. Although the credits for non-ZEVs are lower compared to pure ZEVs, Plug-in Hybrid Vehicles (PHEVs), conventional hybrid vehicles (HEVs), and clean gasoline vehicles qualify for such credits. The mandate allocates “ZEV credits” to the automakers for each vehicle sold and the automakers are required to maintain a certain percentage of ZEV credits of total sales credits year through 2025 (see Table 2.2). For example, an automaker with average sales of 100,000 vehicles between 2014–2016 will require to earn 4500 ZEV credits in 2018 (required ZEV credits in 2018 are 4.5%), this does not directly translate into 4500 ZEVs sold as minimum ZEV floor for 2018 is 2.5%. The manufacturers are allowed to carry over excess credits in a year to subsequent year and can also trade a certain percentage of their credits with other automakers. China introduced a similar mandate in 2017 called the New Energy Vehicle (NEV) mandate (Cui 2018). The NEV mandate calls for each automaker to have a minimum of 10% NEV credits in 2019 and 12% in 2020. The NEV mandate in China also allows the automakers to use their surplus NEV credits for Corporate Average Fuel Consumption (CAFC) compliance, credits trade and credits carry over to next year. The EU has introduced the super-credits system (Regulation (EU) No 333/ 2014) for Low CO_2 Emitting Vehicles (LEVs) (below 50 gCO_2/km) vehicles, and plans to incentivize automakers who surpass their share of ZEVs and LEVs (15% in 2025 and 30% in 2030) with less

Table 2.2 ZEV credit requirement for the automakers selling vehicles in California and nine other US states (CARB 2016)

Model year	ZEV credit requirement (%)	Minimum ZEV credits (%)
2018	4.5	2
2019	7	4
2020	9.5	6
2021	12	8
2022	14.5	10
2023	17	12
2024	19.5	14
2025 and beyond	22	16

stringent CO2 targets. Additionally, EU renewable energy directive II (EU-RED II) (COM//0767 final//0382 (COD) 2016), proposes to make it mandatory for the fuel suppliers to include at least 10% renewables by energy in their fuel blends by 2030, where to qualify as renewable, the fuel must provide 70% CO_2 savings compared to fossil fuels in 2021. In short, many regions across the world are expected to adopt similar aggressive mandates for promoting zero-emissions vehicles in the passenger car sector; however, even in presence of such stringent regulations, based on regulators own estimates, the light-duty fleet will still be a mix of ZEV and non-ZEV vehicles by 2050. In reality, the transition toward complete ZEV vehicles will be slow spanning several decades.

2.2.3 Regulatory Framework for Aviation Sector

Aviation sector accounted for around 11% of oil share in transportation in 2014 and is the fastest growing oil-based transportation sector in terms of energy consumption (IEA 2017). Due to the global nature of aviation business, the civil aviation sector is regulated globally by UN-chartered International Civil Aviation Organization (ICAO). The ICAO during its 39th general assembly in 2016 has introduced a strategy to reduce CO_2 emissions from the aviation sector (ICAO Resolution 2016). The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) proposed in these resolutions call for adopting offset mechanisms to curb CO_2 emissions in the aviation sector. As a part of this mechanism, all aviation operators that emit more than 10,000 tons of CO_2 per year must report their CO_2 emissions from January 1, 2019 for recording average emissions in the 2019–2020 period. The CORSIA mechanism is expected to ensure carbon neutral growth of aviation sector from 2021 by offsetting any CO_2 emissions above the 2020 average baseline. The CORSIA mechanism will be rolled out in phases with the pilot phase from 2021 to 2023 and the first phase from 2024 to 2026, both of which are voluntary. The second phase of this mechanism targets 2027–2035 period where all states with international aviation activities in Revenue Tonne Kilometers (RTKs) in the year 2018 above 0.5% of total RTKs or whose cumulative share in the list of States from the highest to the lowest amount of RTKs reaches 90% of total RTKs must participate. Participation in the second phase is voluntary for the Least Developed Countries (LDCs), Small Island Developing States (SIDS), and Landlocked Developing Countries (LLDCs). There are many ways proposed to offset the CO_2 emissions from aviation using CORSIA which includes financing afforestation, wind energy, clean cookstove, methane capture, and other emissions-reducing or avoidance projects. Additionally, technological, operational, and infrastructure measures are proposed for CO_2 reduction in the aviation sector, however, the aviation sector is set to rely heavily on the CORSIA mechanism and hence is expected to be powered by oil-based jet fuels as the primary energy source. Moreover, the NO_x, SO_x, soot emissions, and the noise pollution are receiving increased attention and are expected to be more regulated in future.

2.2.4 Regulatory Framework for Marine Sector

Marine industry accounted for around 10% of oil share in transportation in 2014 and this share is expected to rise to 16% by 2050 (IEA 2017). The United Nation's chartered International Maritime Organization (IMO) regulates marine transportation globally. Heavy Fuel Oil (HFO), also known as the bunker fuel, intermediate fuel oil, residual fuel oil, is the primary fuel used in the marine sector. The IMO has imposed Sulphur cap on the HFO limiting the Sulphur content to 0.5% m/m (MARPOL Annex VI), which is a sharp decline from the current Sulphur limits of 3.5% m/m. The new Sulphur regulation will come into effect on January 1, 2020. The Sulphur levels in the HFO for vessels operating in the Emission-Controlled Areas (ECAs), the Baltic Sea area, the North Sea area, the North American area (covering designated coastal areas off the United States and Canada), and the United States Caribbean Sea area (around Puerto Rico and the United States Virgin Islands), are further lower at 0.1% m/m. Therefore, in ECAs, most vessels are already operating on more expensive distillate fuels, which have lower Sulphur content. These regulations apply to both main and auxiliary engines and also to any boilers onboard. Sulphur levels in various fuel oils and commonly used distillates are shown in Table 2.3.

The MARPOL Annex VI also regulates the NO_x emissions for seagoing vessels. The NO_x emission levels are set for ships according to engine maximum operating speed levels and are different for old (Tier I, ships in service before January 1, 2000) and new (Tier II, ships constructed after January 1, 2011) vessels, and the vessels operating in NO_x-ECAs (Tier III, ships constructed after January 1, 2016) (see Fig. 2.2).

More recently, IMO has in principle agreed on the initial strategy to reduce the CO_2 footprint of the marine sector by 50% compared to 2008 levels by 2050. This CO_2 reduction is expected to take into account all facets of the marine sector including technological, operational, and fuel/energy source measures update (ITF 2018). The plans may also include market-based offsetting mechanisms for trading CO_2 credits. The IMO plans to revise the agreement by 2023, based on fourth and fifth round of IMO greenhouse gas studies from 2019 to 2022, which would be carried out before drafting any regulations.

Table 2.3 Sulphur content in commonly used fuel oil grades

Common name	ISO name	Typical composition	Typical Sulphur content (%)
Marine Gas Oil (MGO)	DMA	100% distillate	0.1–1.5
Marine Distillate Oil (MDO)	DMB	Distillate with traces of residual oil	0.3–2
Intermediate Fuel Oil 180 (IFO 180)	RME	10% distillate 90% residual oil	2.0–3.5
Intermediate Fuel Oil 380 (IFO 380)	RMG	99% residual oil	3.5

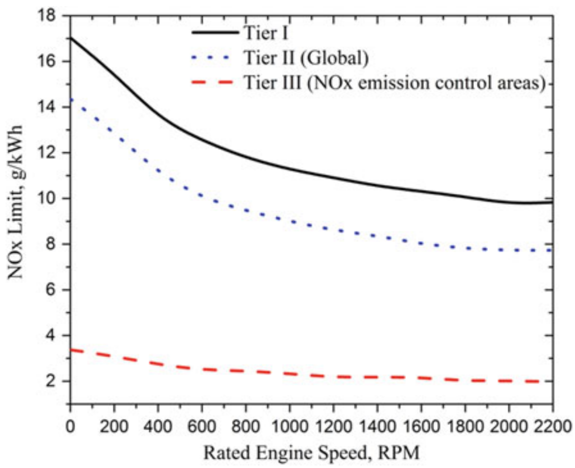

Fig. 2.2 NO_x limit for different tiers as a function of engine speed (McGill and Winther 2013)

2.3 Developments in Transportation Sectors to Meet CO_2 Emission Challenges

2.3.1 Recent Developments in Light-Duty Sector

There are several ways to meet future emission targets in the light-duty sector (Elgowainy et al. 2018). CO_2 emissions can be mitigated by increasing fuel efficiency through advanced gasoline and diesel powertrains, hybridization of ICE and battery, using fuels with low *C*/*H* ratio, using electric and fuel cell vehicles, etc. Among the various options available, the majority of the mainstream automotive manufacturers are choosing the hybridization and electrification route to achieve the futuristic emission goals (Hebert 2017). Although Battery Electric Vehicles (BEVs) do not pollute at the point of use, the pollution caused during electricity generation and in the production and recycling processes of the batteries is often neglected. Since the current regulatory framework for CO_2 emissions of light-duty vehicles is based on the tank-to-wheel emissions (Thiel et al. 2014), BEVs tend to get an unfair advantage over ICE-driven vehicles. In countries or regions where the electricity generation is predominantly based on fossil fuels, especially coal, BEVs can lead to more GHG emissions as compared to the fossil-fuel-driven vehicles (Huo et al. 2015; Faria et al. 2013; Manzetti and van der Spoel 2015). Additionally, a life cycle inventory of BEVs shows increased risk of human toxicity, eutrophication, and metal depletion compared to conventional fossil-fuel-driven vehicles (Hawkins et al. 2013). A more practical issue is the relatively limited driving range, long charging times, short life of battery pack, and lack of charging infrastructure for mainstream BEVs. Improvements in these aspects are an absolute necessity for the widespread adoption of electric vehicles. Therefore, BEVs require more eco-friendly, low-cost, and high energy density batteries to occupy a significant share of the total vehicle fleet. However, despite their current limitations, automotive manufacturers continue to invest in BEVs relying on future potential for improvement in batteries. Additionally, BEVs help the automotive manufacturers in meeting the fleet-averaged CO_2 emission regulations as they are considered as "Zero-Emissions Vehicles" under the current regulatory framework.

A more viable and practical option is to hybridize ICEs for improved fuel efficiency and reduced CO_2 emissions (Elgowainy et al. 2018). Different hybrid options may be suitable for a different class of vehicles within the light-duty sector and hence diversified options are expected moving forward. Series, parallel, and mix hybrid are the various options available currently and each has their own advantages and challenges. Series-hybrid vehicles offer a promising solution of increasing the fuel efficiency in urban driving conditions by allowing the engine to operate under its optimum condition. In such a scheme, ICE will continue to be the primary energy source for the vehicle.

Other options for reducing CO_2 emissions include using fuels with lower carbon to hydrogen ratio. In this case, CNG-driven vehicles become promising due to reduced CO_2 emissions by virtue of their low C/H ratio (Hesterberg et al. 2008). Long-term options include the use of Fuel Cell Vehicles (FCVs) powered by hydrogen or other fuels. Although FCVs have long been touted as the next transportation solution, their market uptake has been slow and they continue to be part of a niche market. However, some of the mainstream vehicle manufacturers are focusing again on fuel cell vehicles and have invested heavily in their research and development (Toyota 2018). The future of hydrogen produced from fossil sources using carbon capture and renewable hydrogen as a fuel, along with fast refueling and long driving range, makes it an attractive and eco-friendly solution. However, the high cost of fuel cell stack and the lack of hydrogen refueling infrastructure are significant bottlenecks currently. Economies of scale are expected to reduce the price of FCVs, however, this is a typical chicken and egg problem. Following Tesla's lead, Toyota has also shared patents related to various aspects of FCV development to accelerate the growth in this segment (Toyota 2018). Additionally, three major Japanese automakers namely Toyota, Honda, and Nissan are cooperating to jointly accelerate the introduction of a hydrogen fueling network by supporting the operation cost and their development.

All the aforementioned medium to long-term options require the development of new fueling infrastructure and/or vehicle modifications and are, therefore, time-consuming and costly to implement. To summarize, there are multiple promising options to achieve future emission targets. However, a holistic cradle to grave analysis needs to be conducted to select an appropriate solution on a case-by-case basis rather than implementing a solution, which merely shifts the burden from one life cycle to another.

2.3.2 Recent Developments in Heavy-Duty Sector

Despite the availability of transportation modes such as rail and shipping, freight and non-urban public transportation will continue to rely on heavy-duty vehicles such as trucks and buses. It is, therefore, vital that the heavy-duty segment should also be equipped with alternative or advanced combustion engine powertrains to contain the increasing carbon emissions. In heavy-duty segment, there are two major changes, i.e., advancement of the combustion powertrain and electrification. In the rest of this section, both of these worldwide trends have been discussed with regards to the heavy-duty segment.

Most of the commercial vehicles around the world use diesel engine as a propulsion system for long-haul road freight truck. To reduce emissions from diesel engine, the thermal efficiency needs to be improved. Initially, when the diesel engine was invented in the 1880s, its efficiency was around 26% and due to continuous improvement in fuel injection systems, engine and piston designs, modern engines exhibit 43–44% thermal efficiency, and it is set to reach 50% by 2030 (Lutsey 2018). The US Department of Energy's Super Truck program is one among various initiatives toward improving the overall performance of heavy-duty segment. The first phase of the Super Truck program was started in 2009 and Cummins, Volvo Group, Daimler Trucks, and Peterbilt were tasked with improving the overall freight efficiency by 50%, quantified in ton-miles per gallon, and engine's brake thermal efficiency by 50%. Super Truck-I (Delgado and Lutsey 2014) program was successful in achieving its goals and the industrial partners even exceeded their commitments (Koeberlein 2014; Stanton 2010; Gibble 2013). The improvements made during the program not only involved powertrain components but also advanced several vehicle components including aerodynamics, transmissions, chassis, air-conditioning, tires, and auxiliaries. As a result, many significant efficiency improvement technologies were developed and are in the process of commercialization, which will further help vehicle manufacturers around the world. To further improve the heavy-duty segment, Super Truck-II (Gilroy 2016; Mulero 2016) was launched in 2016 and brings onboard teams from industry and national labs to research, develop, and demonstrate greater improvement in vehicle freight efficiency thereby cutting down significantly on CO_2 emissions.

EU has taken a less involved approach to improvising the efficiency of heavy-duty vehicles as compared to the US. The EU plans to regulate CO_2 emissions and the targets have been announced in 2018. AEA-Ricardo (AEA-Ricardo 2011) and TIAX (TIAX 2011) reports described extensive research effort by major heavy-duty manufacturers such as Daimler (Daimler 2017), Scania (Scania 2017) and Volvo for increasing diesel engine's efficiency. Major initiatives include improving the combustion system via higher pressure fuel injection systems, reducing engine friction, waste-heat recovery turbo-compounding, and other improvements in the engine such as friction reduction in other parts of the powertrain, redesigning of accessories, etc. These measures are taken continuously to reduce vehicle CO_2 emissions in addition to other developments such as aerodynamics, the increment of bio-component into the fuel blends and hybridization of drivetrains.

2.3.3 Recent Developments in Marine Sector

There are several proposed compliance options to meet the upcoming IMO regulations and aspirations. As far as the availability of 0.5% m/m Low Sulphur Fuel Oil (LSFO) to meet the IMO Sulphur cap is concerned, there have been conflicting reports on the availability of such fuel. A study (Delft 2016) on the availability of compliant LSFO by the IMO chartered CE-Delft reported that all refineries have the capability to supply sufficient quantities of marine fuels with a Sulphur content of 0.50% m/m or less and with a Sulphur content of 0.10% m/m or less to meet demand for these products, while also meeting demand for non-marine fuels. On the other hand, Ensys and Navigistics supplemental marine fuel availability study (Ensys and Navigistics 2016) presented to IMO suggests that the global refining industry will lack sufficient capacity to fully respond to the IMO Sulphur cap resulting in the price increase of not only fuel oil but also distillates and sweeter (low Sulphur) crudes. It is expected that the traditional fuels compliance option will be a mix of distillates (MGO/MDO), LSFO, and their blends; based on the compliance option used, the price for IMO-compliant marine fuels would be significantly more than HFO causing an increase in freight tariffs and will eventually result in some degree of stress on world economy. LNG is proposed as an important alternative option to HFO and LSFO in the marine sector. It offers several advantages; using a gas (LNG)-only engine can reduce the SO_x and soot emissions by almost 100% without further need of after-treatment with manageable NO_x emissions. The CO_2 saving potential of LNG compared to HFO is high (5–30%) but methane slip issues currently reduce the total CO_2 savings (0–20%). Depending on the location, LNG is also price competitive to distillates (MGO/MDO) compliance option with a discount of around $5/MMBtu (OIES 2018a). However, there is a severe infrastructure development barrier that the LNG markets need to overcome for any meaningful marine market penetration and LNG share in marine sector is expected to be around 5% by 2025 (WoodMackenzie 2018).

The other compliance option to meet IMO Sulphur cap is to use scrubber technology for exhaust after-treatment of SO_x emissions. One of the challenges in the uptake of the scrubber technology is the complexity associated with the shipping business. Typically, three to four parties are involved in the entire chain of the shipping business, a shipbuilder who manufactures the ships based on the order by shipowner, the shipowner either directly leases the ships-to-ship charterer or through a middle company to ship charterers who operates the ship. The problem with installing scrubbers is that the ship owners have no incentive to take their ships out of service in the shipyards and also charterers do not see value in paying more up front to the ship owners to make use of low priced HFO which in the long run is a cheaper compliance option. Due to these reasons, scrubber technology is expected to have a limited uptake of around 10–20% by 2020.

Table 2.4 Estimated life cycle CO_2 emissions reduction and current supply and uptake availability of alternative and renewable fuels (adopted from ITF 2018)

Alternative and renewable fuels	CO_2 emissions reduction (%)	Current supply and uptake potential (% of total marine energy)
Advanced biofuels	25–100	0
LNG	0–20	1–2
Hydrogen	0–100	0
Ammonia	0–100	0
Methanol	25–100	0

Several alternative and renewable fuel options are receiving increased attention in the marine sector to meet the upcoming SO_x, NO_x, and CO_2 emissions regulations and aspirations. These include advanced biofuels, LNG, Hydrogen, Ammonia, and Methanol. These options intrinsically produce negligible (well below the 0.5% Sulphur cap) SO_x emissions, manageable NO_x emissions that could be treated using conventional selective catalytic reduction (SCR)-based exhaust after-treatment, and based on the process used for production, can be fully CO_2 neutral. Table 2.4 shows some estimates on CO_2 savings and current supply and uptake potentials of these options for the marine sector. It can be seen from Table 2.4 that although the potential CO_2 savings could be quite significant, depending on the synthesis process of these fuels, the current supply and uptake potential of most of these options, apart from LNG, is quite limited. It is expected that the marine sector will continue to be dominated by oil-based residual and distillate fuels.

Furthermore, various technological and operational measures have been proposed to improve the overall energy efficiency of the marine sector (ITF 2018). The traditional energy efficiency criteria for the new ships is the so-called Energy Efficiency Design Index (EEDI), which measures the CO_2 emissions of the ships and is expected to reduce the CO_2 footprint by 30% by 2030. Other proposed technological measures that are expected to improve the energy efficiency of the ships include using lighter materials to reduce the weight of the ship, slender design for improved hydrodynamics, friction reduction using specialized hull coatings and air lubrication, and incorporating ways to recover waste heat. Operational measures for improving the energy efficiency of the shipping industry include reducing ship speed, increasing ship size, improving the ship–port interface, and providing onshore power at the port.

2.3.4 Recent Developments in Aviation Sector

As explained earlier, the aviation sector is set to rely greatly on the CORSIA mechanism for carbon-neutral growth from 2020. As such, it is expected that oil-based jet fuels will continue to power the aviation sector. The approved Sustainable Aviation Fuels (SAFs) under ASTM D7566, the standard for

Table 2.5 A summary of regulations to curb CO_2 emissions and evolution of technology in various transportation sectors on 1–5 scale

	Light-duty sector	Heavy-duty sector	Marine sector	Aviation sector
Regulations	5	4	1	3
Evolution of technology	5	3	2	2

specifications for aviation turbine fuel containing synthesized hydrocarbons, include Fischer-Tropsch hydro processed synthesized paraffinic kerosene (FT-SPK), synthesized paraffinic kerosene produced from hydro processed esters and fatty acids (HEFA-SPK), synthesized iso-paraffins produced from hydro processed fermented sugars (SIPS-HFS), synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (SPK/A), and alcohol to jet synthetic paraffinic kerosene (ATJ-SPK). These SAFs are expected to be blended in a certain ratio (10–50%) with typical aviation jet kerosene fuels; as such, there are many questions and barriers that need to be overcome by SAFs to have any meaningful market share; there are concerns on the environmental benefits of these fuels (well to wings life cycle footprint), and on the cost and availability of these SAFs.

Overall, it is the light-duty road transportation sector where the regulations are stringent and to meet these regulations most of the innovation in engine/fuel technology is witnessed. Heavy-duty road transportation sector has also seen a surge in legislation for regulating emissions and pollutants and is closely following light-duty segment's lead. The reason for relatively strict regulations for light- and heavy-duty segment stems from the fact that these vehicles have higher visibility in urban and rural spaces where they are often used for transporting people and goods. Additionally, the rapid evolution of technology to meet the regulations has led to tighter regulations in these segments. The regulations in Aviation or Marine sector are still evolving, but several recent developments highlighted in this chapter indicate that tighter legislation will soon be in place. A tabular comparison is presented in Table 2.5 to further summarize the state of regulations and their implementation in various mobility segments on the scale of 1–5 with 5 being highest.

2.4 Technology Trends of Internal Combustion Engines Toward High Efficiency

For the light-duty (LD) passenger transport applications, spark-ignited (SI) engines are mainstream, except Europe, and there is a lot of scope for improvements. The gaseous emissions such as hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NO_x) are treated by three-way catalytic converter with emissions levels being already very low. Therefore, all research directions with SI engines are geared toward the improvement of engine efficiency based on several strategies. The commercial transport applications such as heavy-duty truck, and marine sector rely on compression ignition (CI) engines. CI engine is more efficient than SI engines; however, the emissions of NO_x and soot are higher, and diesel after-treatment is quite expensive. The best possible way to mitigate these emissions would be through in-cylinder phenomenon to achieve low-temperature combustion (LTC) without compromising the efficiency. The other goals pertaining to CI engine research are to maximize the engine efficiency by analyzing the thermodynamic cycles and to develop a fuel-flexible hardware. The trends and recent developments in this context are explained in the following sections.

2.4.1 High-Efficiency SI Engine Research

Ever since the advent of the combustion engine, the thermal efficiency of the ICE has continuously improved. The evolution of efficiency over the past few centuries is depicted in Fig. 2.3. The significant breakthrough came in 1876 from Nikolaus August Otto, who pioneered the invention of an engine that is commonly referred to as a gasoline engine. With the advancement in fuel supply system from the conventional carburetor to port fuel injection (PFI) system, the efficiency improved to 35%. Subsequently, the transition from the PFI system to Gasoline Direction Injection (GDI) system is marked as one of the technological milestones towards higher efficiency in SI engine development (Zhao et al. 1999). The direct injection of fuel into the cylinder with the GDI system reduces the global equivalence ratio, and the cooling effect also adds to improvement in efficiency. In the wake of various engine development strategies, the current efficiency of the SI engine has increased to 42%. Researchers are still in the race to achieve better thermal

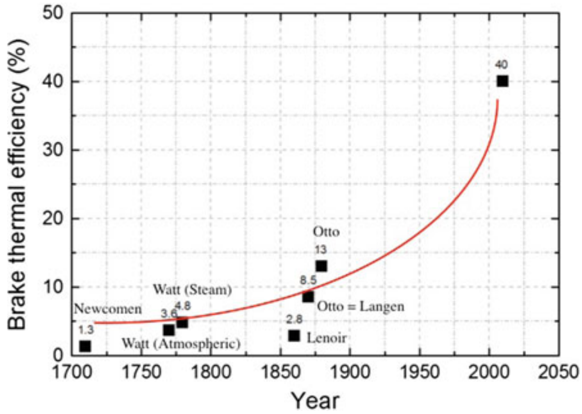

Fig. 2.3 Historical evolution of energy efficiency of a Spark-Ignited (SI) engines

efficiency and the key technology enablers are (1) Engine downsizing (2) Lean burn technology with dilution tolerance, and (3) Government-level initiatives such as the Co-Optima Program.

2.4.1.1 Engine Downsizing

Increasing the compression ratio of the SI engine and diluted combustion are important pathways to improve the efficiency of the engine. However, attaining a maximum compression ratio is limited by engine knock and dilution decreases the burnt rate of combustion. Engine downsizing is an effective approach to improve the efficiency that directly relates to the reduction of carbon footprint (Turner et al. 2014). Despite the smaller displacement volume of the engine, the power output is higher as more air is inducted to burn the fuel through boosting. Reducing the pumping, frictional and heat losses reduce the fuel consumption with the reduced engine out emissions (Avola et al. 2015). The pressure/temperature history of these modern engines are far away from the RON/MON conditions in that the octane rating scale is no longer agreeable. These engines depend on a factor "k", which is a constant in the octane index formulation (OI = RON − $k * S$). The factor "k" is negative for highly boosted downsized engines when knock limited and requires fuels with higher octane sensitivity (Avola et al. 2015). Variable Geometry Turbine (VGT) is a technological advancement in the development of turbocharged engines that allows for a fast transient response to synergize appropriately with the engine (Tang 2016). Currently, Mazda, Ford and Chevrolet, BMW, Mercedes-Benz, and Volkswagen Auto Group have adopted downsized GDI engine with turbocharger technology. The maximum efficiency of the reported commercial engine is 35% and efforts are being taken to further increase the efficiency. This advanced powertrain coupled with hybrid technology is beneficial and Toyota Prius plug-in hybrid electric vehicle showed a brake efficiency of 42%. Dilution through Exhaust Gas Recirculation (EGR) is an effective approach in a turbocharged GDI engine. Diluted combustion relates to stoichiometric operation in boosted downsized gasoline engines and offers greater potential to reduce fuel consumption (Wei et al. 2012). Cooled EGR reduces the engine knock, minimizes pumping losses and avoids the enrichment zones to improve fuel economy. However, the development of flame kernel under heavily diluted condition is difficult and high spark discharge system is recommended. Honda R&D recently demonstrated 45% efficiency using 35% EGR at an engine speed of 2000 rpm with an optimized combustion chamber design (Ikeya et al. 2015). In order to overcome the dilution tolerance and support auto-ignition; higher spark energy of 450 mJ is used. A 3% increase in efficiency when compared to the existing commercial vehicle is a promising improvement.

2.4.1.2 Lean Burn Technology

Lean combustion in SI engines improves the fuel economy and reduces the global CO_2 emissions (Tully 2002; Ayala and Heywood 2007). Moving from stoichiometric to lean mixture increases the specific heat ratio and reduces the pumping losses, which increases the thermal efficiency. However, the disadvantage of this technology is the incompatibility of the catalytic converter at lean conditions. Catalytic converter is effective only at stoichiometric (ø = 1) condition and, therefore, the use of lean technology leads to increased HC and CO emissions. The main problem with the lean combustion technology is the inadequacy of the ignition energy supplied from the spark plug. As the mixture is lean, the ignition energy is increased to improve the combustion stability and tolerate the dilution level (Shah et al. 2012; Toulson et al. 2010). Thus, development and characterization of the ignition system for lean-burn SI engines are crucial.

In a measure to adopt lean combustion technology in modern gasoline engines, Turbulent Jet Ignition (TJI) through pre-chamber combustion system was proposed (Alvarez et al. 2017). While the spark energy is not sufficient to burn the lean mixture in a gasoline engine, Turbulent Jet Ignition (TJI) is favorable to support lean combustion. The pre-chamber system is incorporated in place of a spark plug in the cylinder head. Initially, the TJI concept was applied for operation of natural gas in an SI engine to improve the efficiency (Attard et al. 2012a). Currently, gasoline only system substitutes the use of natural gas with improved durability (Attard et al. 2012b). According to the pre-chamber concept that functions with gasoline alone, a small quantity of liquid fuel is injected in the pre-chamber. In the main combustion chamber, fuel is directly injected early in the cycle so that a lean mixture is formed. Given the volume of pre-chamber is only 3% of the main combustion chamber, a rich mixture is burnt in the pre-chamber to create a stratified charge. The more active radicals of the burnt mixture in the pre-chamber pervade as turbulent jets into the main combustion chamber and create multiple ignition sites. This turbulent jet has more active energy compared to the spark energy and increases the mass burnt rate. The increased flame propagation extends the knock limit that helps to improve the efficiency. MAHLE powertrain showed an ultra-lean homogeneous combustion ($\lambda \sim 1.6$) with an efficiency of 42.8% based on a new design of pre-chamber system in a gasoline engine (Bunce and Blaxill 2016). Since knock is limited, the compression ratio of the engine can be increased (hardware upgrade) to further increase the efficiency up to 45%. Based on pre-chamber jet ignition system, HONDA (i-CVCC) demonstrated an efficiency of 47.2%. These technologies would be commercialized in the near future so that the benchmark to compete with would be a higher efficiency of around 48–50%.

2.4.1.3 Government Level Initiatives (Co-optima Program)

The Co-Optima Program aims to introduce clean, efficient, and high-performance engine by establishing synergy between fuel and engine technologies (U.S. DOE

2016). The Co-Optima approach helps to identify a new blend-stock that can be blended with gasoline to improve the performance of the vehicle and reduce the emissions. The selection of blend-stock from domestic resources delineates to cellulosic biomass, renewable, nonfood, and surplus resources. The blend-stock is evaluated based on the fuel properties and design parameters that maximize the efficiency of the engine through mitigation of knock. Research Octane Number (RON), octane sensitivity (S = RON − MON), and heat of vaporization are the important properties that improve knock resistance of modern SI engines. For achieving these favorable properties, the chemical families identified are alcohols, ketones, furans, alkenes, and aromatics. The blend-stock produced from any of these families when blended with gasoline improves efficiency. Before blending, the compatibility of these blend-stocks on engine infrastructure is screened. Furthermore, system-level analysis of these blend-stocks with respect to economic, technological, market, and environmental factors is performed. The gasoline blended with the blend-stock when operated in a boosted SI engine results in a highly efficient co-optimized fuel/engine system. The Co-Optima researchers demonstrated a direct correlation between knock performance and Octane Index (OI), which is a crucial derived property (OI = RON – k * S). While Low-Speed Pre-Ignition (LSPI) limits the engine efficiency, measures to identify and prevent pre-ignition occurrence for various gasoline blends under boosted conditions are essential. Computational analysis based on numerical algorithms and validated engine models provide insights into the development of the engine, which cannot be operated in a laboratory scale due to practical limitations. The co-optimized engine operated under multi-mode combustion concept is the next step to further increase the efficiency. Overall, fuel properties and advanced combustion concepts help to improve engine efficiency, and programs like Co-Optima could facilitate the identification of an optimum fuel-engine combination.

2.4.2 High-Efficiency CI Engine Research

Diffusion-controlled spray combustion leads to the formation of increased NO_x and soot emissions in a CI engine. Today's commercial medium and heavy-duty fleets adopt the Mixing-Controlled Compression Ignition (MCCI) concept for gaining higher efficiency but require effective emission control technologies. The diesel after-treatment utilizes Selective Catalytic Reduction (SCR) and particulate filter to reduce the NO_x and particulate matter emissions, whereas HC and CO emissions are treated by Diesel Oxidation Catalyst (DOC) (Johnson 2010). These after-treatment devices are much more complex and expensive when compared to the three-way catalytic converter in SI engines. High-pressure Common Rail fuel Direct Injection (CRDI) system is a pioneering technology to improve the fuel atomization and air/fuel mixing. However, the advancement from mechanical injection to CRDI system could not mitigate the deleterious emissions of NO_x and PM. Measures to overcome the NO_x/soot tradeoff have been up-taken over several decades and paved the way to the development of new combustion concepts. Instead of after-treatment technique, advanced combustion concepts such as Homogenized Charge Compression Ignition (HCCI) and Partially Premixed Combustion (PPC) are proposed for simultaneous reduction of NO_x and soot emissions (Zheng 2009; Noehre et al. 2006). Furthermore, these combustion strategies also improve the efficiency due to low-temperature combustion (minimized heat loss), which mitigates the CO_2 emission. Besides new combustion concepts, the thermodynamic cycle analysis to realize higher efficiency has been investigated and researched. The eight-stroke engine is the latest technology that improves the thermodynamic process to reduce the heat losses and allows for efficiency improvements. These renewed combustion concepts that aim to achieve 60% efficiency are current research initiatives pertaining to CI engine technology.

2.4.2.1 High-Efficiency Combustion Concepts

Few in-cylinder combustion strategies proposed to mitigate NO_x and soot emissions without compromising engine efficiency are HCCI, PPC, and Reactivity-Controlled Compression Ignition (RCCI) (Sarangi 2012). These Low-Temperature Combustion (LTC) concepts reduce the local flame temperature and equivalence ratio in such a way that NO_x and soot formation are reduced simultaneously. When the Start of Injection (SOI) is advanced from late to early fuel injection timings, combustion drifts from CI toward HCCI condition (Vallinayagam et al. 2017). In HCCI mode, fuel and air are completely premixed during the significant delay period and combustion is controlled by mixture chemical kinetics. Given that the controllability of combustion is a problem at high load with HCCI due to rapid pressure rise rate; studies on PPC emerged that effectively controls combustion due to increased combustion stratification (Najafabadi 2017). While combustion phasing is sensitive to SOI in CI combustion, it is dependent on intake air temperature for HCCI combustion. PPC is intermediate between HCCI and CI combustion in that the fuel injection is crucial for controlling the combustion phasing. In 2001, Nissan Motor Company investigated diesel PPC through modulated kinetics combustion concept (Kimura et al. 2001). Based on EGR, the required ignition delay was created at various loading conditions. Due to low temperature and premixed combustion, a simultaneous reduction in NO_x and soot emission was achieved. The high load diesel operation demanded 70% EGR, which deteriorated the combustion process. Given that diesel PPC was not advantageous at all the operating ranges, gasoline PPC was introduced in 2006 (Kalghatgi et al. 2006). When fuels with resistance to auto-ignition are used in CI engines, they create an adequate delay period for premixing; this decreases the in-cylinder temperature to suppress NO_x formation, while local fuel to air equivalence ratio is decreased to reduce soot emission. Gasoline PPC is also described as Gasoline Compression Ignition (GCI), which has grabbed more attention in the past decade and most of the engine manufacturers are in the endeavor to commercialize the first GCI engine.

Ignition assistance is required to support the auto-ignition and maintain combustion stability when using high RON gasoline fuels in a Compression Ignition (CI) engine. However, high RON fuels prove difficult to auto-ignite at low load condition, as the available boost is limited (Manente et al. 2009). In the current scenario, low-load GCI is a big challenge and efforts are being made to improve the combustion stability. Selection of low RON gasoline could avert this problem and RON 70 gasoline is an ideal candidate for GCI investigation (Solaka et al. 2012). Naphtha (a low octane gasoline fuel with RON $\sim$ 60–70) has been tested as a suitable fuel for GCI engines (Alabbad et al. 2018; Leermakers et al. 2013) due to its suitable fuel properties such as its optimal reactivity to ignite under compression, low well-to-tank carbon footprint due to reduced refinery processing and higher H/C ratio (due to paraffinic composition) ascertaining lower tank-to-wheel carbon emissions. Furthermore, based on its boiling point (BP), naphtha can be categorized as light (BP = 75 °C) or heavy (BP = 175 °C). Since it is a less-processed fuel, less refining energy is required thereby reducing production costs; it is also less intensive in terms of reduced well-to-tank CO_2 emission. The vehicular demonstration of naphtha in a PPC engine demonstrated improved fuel economy and better combustion stability at low load condition (Chang et al. 2013). Thus, low-load operation of GCI is possible without any auto-ignition problems using low RON gasoline or naphtha. However, the low RON gasoline fuels are not commercially available and adaption of these fuels could be a choice in the future. At present, high RON gasoline is being used commercially and strategies to overcome auto-ignition problems and enable low load and idle operation are essential. In this respect, Delphi is involved in the development of Gasoline Direct injection Compression Ignition (GDCI) engine using US market gasoline (Sellnau et al. 2014, 2016). The fuel injection strategy was optimized in such a way to achieve PPC at very low fuel injection pressure, typical of GDI engines. Delphi electrical cam phaser's actuated the exhaust valve train to enable secondary valve lift, recuperating heat from hot exhaust gases to support auto-ignition at low loads. Retaining the residuals helps to reduce the oxygen flow rate and local flame temperature with increased heat capacity. The longer ignition delay also influences the local fuel to air equivalence ratio. As such, both NO_x and soot emissions are simultaneously reduced. Measures to control the combustion by spark assistance provided a better solution (Manofsky et al. 2011). Spark-assisted GCI is the evolving technology toward the extension of low load limit until now (2018). A recent innovative combustion concept called Spark-Assisted Compression Ignition (SACI) of gasoline was introduced by MAZDA (2018). With Mazda's Skyactive-X is ready for launch on 2019, it is touted as the world's first commercial gasoline engine running on compression ignition mode.

The pictorial layout in Fig. 2.4 elucidates the different high-efficiency combustion concepts that have been identified thus far.

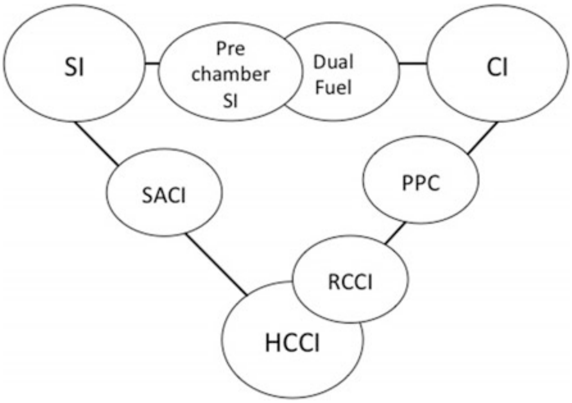

Fig. 2.4 Advanced high-efficiency combustion concepts for ICE

2.4.3 Eight-Stroke Engine Concept (High-Pressure Combustion)

Eight-stroke concept is a staged engine concept and is an alternative step to achieve up to 60% engine efficiency (Lam et al. 2015). Staged or complex engines have been around for over a century. Most powertrains are staged engines with a rotary compressor and expander before and after the piston machine. The reason to assess replacing these rotary units with piston machines is the greater efficiency of piston machines at volumes that are typical of light- and heavy-duty engines. The challenge to attain maximal efficiency from this architecture requires a thorough understanding of inherent loss mechanisms. The 1D modeling of such complex devices provides us a design tool to evaluate the performance of such a device with various design features such as staging ratios, insulation, modifications to air path, and combustion concepts (Shankar et al. 2017, 2018). The development of any high-efficiency system must also consider the boundary conditions for an effective after-treatment system, which is also evaluated using 1D gas exchange models. The concept is a bit down the road from being fully realized as only a demonstrably superior efficiency compared to present architectures could convince manufacturers to adopt this technology.

2.5 Disruptions in Transportation Sector and Policy Implications

Transportation sector is going through a major disruption phase and personal mobility is on the cusp of change from what we have known for the past 50 years or so, and such disruptions are most evident in the LDV road transportation sector. Electrification and hybridization are important disruption agents (OIES 2018b). In recent years, several new technologies have featured in the otherwise ICE-dominated

LDV road transport sector. These include HEVs, PHEVs, BEVs, and FCVs. Of these technologies, HEVs and PHEVs, depending on the mode of operation (e.g., charge sustaining versus charge depleting modes in PHEV), still rely heavily on ICE as primary energy source in the vehicle, and only the BEVs, typically of limited driving range, are powered by fully electrified powertrains; nonetheless, it has to be acknowledged that pure ICE vehicle models, without any hybridization or electrification, may well be phased out from the LDV sector in the next 15–20 years time frame. In much of the popular media, such disruptions, in one form or the other, are readily linked to an eventual demise of oil-based ICE-powered vehicles. Such a hype should be evaluated cautiously as the technologies go through many hype and disappointment cycles before they make a major impact in the market or die down (Melton et al. 2016). Kalghatgi in his recent work tried to answer some of the hype associated with this notion in his paper titled "Is it really the end of internal combustion engines and petroleum in transport?" (Kalghatgi 2018). He argues that, for LDVs, available battery capacity will have to increase by several hundred-fold, perhaps by several thousand-fold, for complete electrification. This will have serious economic, social, environmental, and political impacts and, as such, is highly unlikely in near future. In addition, the requirements for complete electrification of HDVs are even more stringent (Kalghatgi 2018; Sripad and Viswanathan 2017), and are so extreme for marine and aviation, that proposing such electrified solutions for them, even in the presence of current media hype, should be backed up by thorough, unbiased and scientific analyses of which nothing could be found in literature. Hence, unless renewable electricity becomes abundantly available and price competitive, the massive infrastructure requirements for electrification are dealt with, and the battery capacities and costs dramatically improve to meet the transportation needs, transportation sector is expected to be powered by oil-based solutions, in one form or another, particularly for HDVs, marine, and aviation, for the foreseeable future. Hybridization of ICE vehicles is the most probable way forward for improving the efficiency and environmental footprint of ICE-only vehicles, and the transition of transportation, even for LDVs, to complete electrification will be evolutionary and not disruptive spanning several decades.

The other disruptive agents in the transportation sector, again primarily in the LDV sector, are the emergence of shared mobility and autonomous vehicles (OIES 2018b). The Ubers, the Lyfts, the Careems, etc., model of transportation as a service has certainly received widespread acceptance since such a model allows the consumers to have a ride ready whenever and wherever they want without worrying too much about the problems (parking, refueling, service, maintenance, insurance, etc.) associated with the transportation ownership model. The advent of shared mobility model and the autonomous vehicles also combine well with each other and it is expected that in future, especially in big metropolises, these two disruptive agents will steadily overtake the transportation ownership model. The cost of such rides per kilometer are expected to come down; and although the transportation as a service model and autonomous vehicles will improve the traffic congestion and problem related to ever-increasing cars, the total number of kilometers are expected to be increased because of the ease of use offered by such models (OIES 2018b). The profit margin and continuous vehicle availability are expected to be among major considerations of the vehicle/fleet operators under transportation as a service model, again, complete electrification of the LDV fleet in such a model could only be realized if the electric cars become price competitive and the charging times and the mileage of BEVs significantly improve. Fleet operators will also closely monitor all of these parameters for the scenarios where the government provided subsidies for electric vehicles and battery charging dry out.

In addition to the disruptions discussed above, some countries have announced their aspirations to ban ICE-only vehicles. Such aspirations are meant to curb the pollutants related to local air quality, the NO_x, SO_x, CO, HCs and soot emissions, and the climate change. The governments of UK, France, China, India, Germany, along with city administrators of major metropolises including Paris, Barcelona, Madrid, have expressed aspirations to ban ICE only vehicles in 2030–2040 time-frame. Most of these aspirations are announced in the popular media without formal government-level proposals or regulations drafted thus far. Implicit in these news is the fact that most of these countries, although aspire to ban ICE-only vehicle, will still continue to use combustion engine hybridized in one form or another as a primary energy source for the vehicles. It is beyond question that transportation must do more to improve its environmental footprint. However, it is equally important that the governments and regulators, instead of picking the winners, take a balanced and informed approach while formulating policies and regulations for the transportation sector. Life Cycle Analysis (LCA)-based policies and decision-making (Abdul-Manan 2018) should be adopted to arrive at scientifically backed policies and practical solutions to improve the environmental impact of the transportation sector. All the technological options should be properly evaluated utilizing LCA-based methodologies to arrive at a sustainable transportation model for the future. Policy makers and regulators must avoid simple burden shifting as such short-sighted approaches may alleviate the pollution concerns in the cities but may not overcome the climate change concerns globally.

2.6 Conclusions

The mobility of man and goods accounts for around a quarter of greenhouse gas emissions globally and, therefore, naturally attracts the most stringent regulations for emissions and fuel efficiency. Here, current and prospective regulatory framework for road, marine, and aviation transport sectors, aimed at curbing the CO_2 emissions from the transportation is presented. It is shown that the fuel economy and CO_2 emission targets are becoming stricter across the various transportation sectors. For light-duty sector, such regulations are even more stringent and the recent introduction of zero-emission mandates is forcing the OEMs to invest more in hybridization and electrification. The available compliance options for various transport sectors are also discussed. Holistically speaking, the fossil fuel powered combustion engines/turbines are expected to continue powering the transport sector for decades to come. The passenger transport sector is expected to have a slow transition, spanning several decades, towards electrification. Several advanced engine technologies, with the potential to improve fuel economy and CO_2 emissions, including highly boosted and downsized SI engine concepts, pre-chamber SI engine concept, 8-stroke and GCI/PPC CI concepts are briefly discussed. Various disruption agents are presented, especially in the light-duty sector, and it is expected that the personal mobility models may change in the near future. Finally, it is argued that a LCA-based policy must be adopted for proposing any future regulations for the transport sector.

References

Abdul-Manan AF (2018) On the appropriate use of life-cycle thinking for evidence-based sustainable transport policy. Environ Sci Policy Sustain Dev 60:18–25

AEA-Ricardo (2011) Reduction and testing of greenhouse gas emissions from heavy duty vehicles-LOT 2. Development and testing of a certification procedure for CO_2 emissions and fuel consumption of HDV, report by AEA and RIcardo

Alabbad M, Issayev G, Badra J, Voice AK, Giri BR, Djebbi K, Ahmed A, Sarathy SM, Farooq A (2018) Autoignition of straight-run naphtha: a promising fuel for advanced compression ignition engines. Combust Flame 189:337–346

Alvarez CEC, Couto GE, Roso VR, Thiriet AB, Valle RM (2017) A review of prechamber ignition systems as lean combustion technology for SI engines. Appl Therm Eng

Attard WP, Toulson E, Huisjen A, Chen X, Zhu G (2012a) Spark Ignition and pre-chamber turbulent jet ignition combustion visualization. SAE Technical Papers

Attard WP, Blaxill H, Anderson EK, Litke P (2012b) Knock limit extension with a gasoline fueled pre-chamber jet igniter in a modern vehicle powertrain. SAE Int J Engines 5(3):1201–1215

Avola C, Copeland T, Duda R, Burke S, Akehurst CB (2015) Review of turbocharger mapping and 1D modeling inaccuracies with specific focus on two-stag systems. SAE Technical Paper Report No 0148–7191

Ayala FA, Heywood JB (2007) Lean SI engines: the role of combustion variability in defining lean limits. SAE Technical Papers

Bunce M, Blaxill H (2016) Sub-200 g/kWh BSFC on a light duty gasoline engine. SAE Technical Paper

CARB (2016) Zero-emission vehicle standards for 2018 and subsequent model year passenger cars, light-duty trucks, and medium-duty vehicles, California Air Resource Board

Chang J, Kalghatgi G, Amer A, Adomeit P, Rohs H (2013) vehicle demonstration of naphtha fuel achieving both high efficiency and drivability with EURO6 engine-out NOx emission. SAE Int J Engines 6(1):101–119

COM//0767 final//0382 (COD) (2016) Proposal for a directive of the European parliament and of the council on the promotion of the use of energy from renewable sources (recast), COM//0767 final//0382 (COD)

COM//284 (EU) (2015) Proposal for a regulation setting CO_2 emission performance standards for new heavy-duty vehicles

Cui H (2018) China‘s new energy vehicle mandate policy (Final Rule). Policy update. ICCT report

Daimler (2017) Diamler Sustainability focus report, Diamler 2017

De Groot GJ (1996) Blighty: British society in the era of the great war. Addison-Wesley Longman

Delft (2016) Assessment of fuel oil availability, Final report, CE Delft, July 2016

Delgado O, Lutsey N (2014) The U.S. SuperTruck program: expediting development of advanced HDV efficiency technologies
Elgowainy A, Han J, Ward J, Joseck F, Gohlke D, Lindauer A, Ramsden T, Biddy M, Alexander M, Barnhart S, Sutherland I, Verduzco L, Wallington TJ (2018) Current and future united states light-duty vehicle pathways: cradle-to-grave lifecycle greenhouse gas emissions and economic assessment. Environ Sci Technol 52(4):2392–2399
EnSys and Navigistics (2016) Supplemental marine fuel availability study to the IMO, EnSys and Navigistics, July 2016
EPA (2017) Carbon dioxide emissions and fuel economy trends report, US EPA 2017
EU (2018) Monitoring of CO_2 emissions from passenger cars—Regulation (EC) No 443/2009
Faria P, Marques P, Moura F, Freire J, Delgado AT, de Almeida R (2013) Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renew Sustain Energy Rev 24:271–287
Garg M, Sharpe B (2017) Fuel consumption standards for heavy-duty vehicles in India, ICCT report
Gibble K (2013) Scattering of cold-atom coherences by hot atoms: frequency shifts from background-gas collisions. Phys Rev Lett 110(18):180802
Gilroy RW (2016) SuperTruck II aims to more than double freight efficiency of Class 8s
Hanemann M (2008) California's new greenhouse gas laws. Rev Environ Econ Policy 2(1):114–129
Hawkins TR, Singh B, Majeau Bettez G, Strømman AH (2013) Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):53–64
Hebert A (2017) Developing future light-duty vehicle regulations in California, CARB 2017
Hesterberg TW, Lapin CA, Bunn WB (2008) A comparison of emissions from vehicles fueled with diesel or compressed natural gas. Environ Sci Technol 42(17):6437–6445
Huo H, Cai H, Zhang Q, Liu F, He K (2015) Life-cycle assessment of greenhouse gas and air emissions of electric vehicles: a comparison between China and the U.S. Atmos Environ 108:107–116
ICAO Resolution A39-2 (2016) Consolidated statement of continuing ICAO policies and practices related to environmental protection—climate change and global market-based measure (MBM) scheme, 39th ICAO Assembly
IEA (2017) Energy technology perspectives. http://www.iea.org/etp/explore/
Ikeya K, Takazawa M, Yamada T, Park S, Tagishi R (2015) Thermal efficiency enhancement of a gasoline engine. SAE Int J Engines 8
ITF (2018) Decarbonizing maritime transport: pathways to zero-carbon shipping by 2035. OECDs International Transport Forum (ITF)
Johnson TV (2010) Review of diesel emissions and control. SAE Int J Fuels Lubr 3:16–29
Kalghatgi G (2018) Is it really the end of internal combustion engines and petroleum in transport? Appl Energy 225:965–974
Kalghatgi GT, Risberg P, Ångström HE (2006) Advantages of fuels with high resistance to auto-ignition in late-injection, low-temperature, compression ignition combustion. SAE Technical Paper
Kimura K, Tsukahara K, Usui T, Okuda J, Kitamura Y, Kosuge M, Sano T, Tohyama S, Yamanaka O, Yoshii Y, Umemura S (2001) Low-dose tissue plasminogen activator followed by planned rescue angioplasty reduces time to reperfusion for acute myocardial infarction treated at community hospitals. Jpn Circ J 65(10):901–906
Kline SJ, Rosenberg N (2009) An overview of innovation, Studies on Science and the Innovation Process, pp. 173–203 (2009)
Koeberlein D (2014) Technology and system level demonstration of highly efficient and Class 8 trucks, Cummins Super Truck Program
Lam N, Tuner M, Tunestal P, Andersson A, Lundgren S (2015) Double compression expansion engine concepts: a path to high efficiency. SAE Int J Engines 8
Leermakers CAJ, Bakker PC, Somers LMT, Goey L, Johansson BH (2013) Butanol-diesel blends for partially premixed combustion. SAE Int J Fuels Lubr 6(1):217–229

Lutsey N (2018) The ever-improving efficiency of the diesel engine, ICCT report
Manente V, Johansson B, Tunestal P, Cannella W (2009) Effects of different type of gasoline fuels on heavy duty partially premixed combustion. SAE Int J Engines 2(2):71–88
Manofsky L, Vavra J, Assanis DN, Babajimopoulos A (2011) Bridging the gap between HCCI and SI: spark-assisted compression ignition. SAE Technical Paper
Manzetti S, van der Spoel D (2015) Impact of sludge deposition on biodiversity. Ecotoxicology 24 (9):1799–1814
MAZDA (2018) Next-generation Skyactive-X gasoline engine. MAZDA
McGill WR, Winther K (2013) Alternative fuels for marine applications, from the motor fuels implementing agreement. A report from the IEA advanced motor fuels
McNeil I (2002) An encyclopedia of the history of technology, Routledge Companion Encyclopedias
Melton N, Axsen J, Sperling D (2016) Moving beyond alternative fuel hype to decarbonize transportation. Nat Energy 1(3)
Mitchell J Jr, Dzerdzeevskii B, Flohn H, Hofmeyr W, Lamb H, Rao K, Wallen C, Mitchell Wallen J (1966) Climate change. World Meteorological Organisation Technical note
Morris I (2015) The unexpected origin of human values. New Sci 226(3017):28–31
Mulero E (2016) DOE debuts 2nd phase of SuperTruck; pledges $80 million to efficiency effort. American Trucking Associations. ISSN: 0041–1558
Najafabadi MI (2017) Optical study of stratification for partially premixed combustion, PhD thesis, Technische Universiteit Eindhoven 2017
Noehre C, Andersson M, Johansson B, Hultqvist A (2006) Characterization of partially premixed combustion. SAE Technical Paper
OIES (2018a) A review of demand prospects for LNG as a marine transport fuel, The Oxford Institue for Energy Studies
OIES (2018b) Disruptive change in transport sector. The Oxford Institute for Energy Studies
Regulation (EU) No 253 (2014) European Parliament and of the Council amending Regulation (EU) No 510/ to define the modalities for reaching the target to reduce CO_2 emissions from new light commercial vehicles (2014)
Regulation (EU) No 333 (2014) European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO_2 emissions from new passenger cars
Sarangi A (2012) Diesel low temperature combustion: an experimental study. Loughboro University
Scania (2017) Scania sustainability report, Scania 2017
Sellnau M, Foster M, Hoyer K, Moore W, Sinnamon J (2014) Development of a gasoline direct injection compression ignition (GDCI) Engine. SAE Int J Engines 7(2):835–851
Sellnau M, Foster W, Moore J, Sinnamon K, Hoyer W, Klemm M (2016) Second generation GDCI multi-cylinder engine for high fuel efficiency and US tier 3 emissions. SAE Int J Engines 9:1002–1020
Seyferth D (2003) The rise and fall of tetraethyllead. 1. Discovery and slow development in european universities, 1853–1920. Organometallics 23(5):2346–2357
Shah A, Tunestal P, Johansson B (2012) Investigation of performance and emission characteristics of a heavy duty natural gas engine operated with pre-chamber spark plug and dilution with excess air and EGR. SAE Int J Engines 5(4):1790–1801
Shankar VSB, Lam N, Andersson A, Johansson B (2017) Optimum heat release rates for a double compression expansion (DCEE) engine. SAE Technical Paper
Shankar B, Shankar V, Johansson B, Andersson A (2018) Double compression expansion engine: a parametric study on a high-efficiency engine concept. SAE Technical Paper Series
Solaka SA, Boshamer SE, Parworth CL, Heard GL, Setser DW, Holmes BE (2012) Isomerisation of CF2ClCH2Cl and CFCl2CH2F by interchange of Cl and F atoms with analysis of the unimolecular reactions of both molecules. Chemphyschem Eur J Chem Phys Phys Chem 13 (3):869–878

Splitter DA, Pawlowski A, Wagner R (2016) A historical analysis of the co-evolution of gasoline octane number and spark-ignition engines. Front Mech Eng 1

Sripad S, Viswanathan V (2017) Performance metrics required of next-generation batteries to make a practical electric semi truck. ACS Lett 2:1669–1673

Stanton D (2010) High efficient clean combustion for SuperTruck. DEER 2010

Tang H (2016) Application of variable geometry turbine on gasoline engines and the optimisation of transient behaviours

Thiel C, Schmidt J, Zyl AV, Schmid E (2014) Cost and well-to-wheel implications of the vehicle fleet CO_2 emission regulation in the European Union. Transp Res Part A 63(4):25–42

TIAX (2011) European union greenhouse gas reduction potential for heavy-duty vehicles, prepared by TIAX for ICCT

Toulson E, Schock HJ, Attard WP (2010) A review of pre-chamber initiated jet ignition combustion systems. SAE Technical Paper

Toyota (2018) New vehicle zero CO_2 emissions challenge, Toyota Environmental report 2018

Transport Dept (2012) 2017–2025 model year light-duty vehicle greenhouse gas emissions and corporate average fuel economy standards, US Department of Transport

Transport Dept (2016) Greenhouse gas emissions and fuel efficiency standards for medium- and heavy-duty engines and vehicles—phase 2, US Department of Transport

Tully L (2002) A universal view of data. Interview by Anne Zender. J AHIMA 73(10):92

Turner JWG, Popplewell A, Richardson S, Lewis AGJ, Akehurst S (2014) Ultra boost for economy: realizing a 60% downsized engine concept. SAE Int J Engines 7:387–417

Tushman ML (1997) Winning through innovation. Strat Leadship 25(4):14–19

UNFCC (1992) United Nations framework convention on climate change. United Nations New York

UNFCC (2015) United nations framework convention on climate change, Paris, France

U.S. DOE (2016) Co-optimization of fuels & engines, US Department of Energy 2016

Vallinayagam R, Vedharaj S, An Y, Dawood A, Najafabadi MI, Somers B, Johansson B (2017) Combustion stratification for naphtha from CI combustion to PPC. SAE Technical Paper

Wei H, Zhu T, Shu G, Tan L, Wang Y (2012) Gasoline engine exhaust gas recirculation—a review. Appl Energy 99(2):534–544

WoodMackenzie (2018) IMO 2020 updated analysis of the marine fuel sulphur changes. https://www.woodmac.com/reports/refining-and-oil-products-imo-2020-updated-analysis-of-the-marine-fuel-sulphur-changes-18902

Yang Z, Bandivadekar A (2017) Light-duty vehicle greenhouse gas and fuel economy standards. ICCT report

Yao Z, Zheng HML (2009) Progress and recent trends in homogeneous charge compression ignition (HCCI) engines. Prog Energy Combust Sci 35:398–437

Zhao F, Lai MC, Harrington DL (1999) Automotive spark-ignited direct-injection gasoline engines. Prog Energy Combust Sci 25:437–562