



# Chapter 2

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

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

**Abstract** The transportation sector accounts for around a quarter of global CO<sub>2</sub> emissions and is powered predominantly by fossil-derived fuels. The regulatory framework is evolving globally to more stringent requirements for fuel efficiency and CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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](mailto: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. Alqaity  
Institute for Combustion Technology, RWTH Aachen University,  
52056 Aachen, Germany



27 **Keywords** Transport • Climate change • Fuel economy • CO<sub>2</sub>  
28 Regulations • ZEV • Aviation • Marine • LCA

## 30 2.1 Introduction

### 31 2.1.1 History

32 Combustion of fuels has been a dominant source of energy for mankind since ages.  
33 In primitive times, wood was the major fuel used for heating, lighting, and cooking  
34 purposes. As mankind's understanding of their surroundings grew, the focus shifted  
35 to an improved version of fuels such as coal, marking the beginnings of the fossil  
36 fuel era (Morris 2015). Coal-offered significant advantages over wood such as  
37 higher energy density, better flammability, etc., making it a fuel of choice for  
38 heating, lighting, and even powering mobility. Locomotives with coal-powered  
39 steam engines were introduced in the eighteenth century and became popular  
40 (McNeil 2002). Arguably, a paradigm shift in mobility came along when Nikolaus  
41 Otto patented his 4-stroke engine in 1876 (Wayne 1970) along with Gottlieb  
42 Daimler and Wilhelm Maybach, which used one of the light fractions from crude  
43 oil distillation as fuel (Morris 2015). Henry Ford eventually reinforced the signif-  
44 icance of this discovery in 1908 when he introduced the first mass-produced  
45 affordable vehicle, Model-T (Wayne 1970). This innovation, along with other  
46 similar developments in the European markets (Dutton 2006), revolutionized the  
47 personal mobility sector leading to its wide acceptance among common people.  
48 Despite enabling freedom of movement for the mass population, the early vehicles  
49 were riddled with issues such as poor fuel efficiency, low power density, and were  
50 very high on carbon emissions (Dutton 2006). These shortcomings became more  
51 evident (De Groot 1996; Tushman 1997; Kline and Rosenberg 2009) when the  
52 World Wars broke out in Europe and to support the war effort, fuel efficient and  
53 high powered vehicles were needed. One inhibitor in improving the fuel efficiency  
54 of these engines was their low compression ratio, which was limited by engine  
55 knock (Seyferth 2003). Fuels at that time had lower octane numbers because of  
56 limited advancement in refinery processes (Splitter et al. 2016) such as catalytic  
57 reforming, cracking, etc. Amid attempts on engine and fuel improvement in the  
58 1920s, a young engineer Thomas Midgley and his associates came up with the  
59 suggestion of blending small quantities of Tetra Ethyl Lead (TEL) to the gasoline to  
60 increase its knock resistance and hence allowing engines to deliver higher power  
61 and better efficiency in the process. However, due to health and environmental  
62 impacts of TEL, it was phased out in the 1970s around major parts of the world,  
63 thereby affecting the automotive efficiency adversely (Splitter et al. 2016). Soon  
64 after, automotive manufacturers started using electronic fuel injection system and  
65 engine management software, which revived engines' performance to TEL levels.

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

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

84 Since then, two meetings of UNFCC have had a significant impact in shaping  
85 global climate change policies. In 1997, during Kyoto summit (UNFCC 1992), it  
86 was decided that the participating states will strive to reduce greenhouse gas  
87 emissions based on the scientific consensus that global warming is occurring and it  
88 is extremely likely due to anthropogenic CO<sub>2</sub> emissions. During the second meeting  
89 in Paris, an agreement to keep the increase in global average temperature to well  
90 below 2 °C above pre-industrial levels was reached (UNFCC 2015); in addition to  
91 the consensus to limit the increase to 1.5 °C to substantially mitigate the risks  
92 associated with climate change.

### 93 **2.1.2 Overview**

94 The agreements ratified at these meetings were executed in different versions across  
95 major parts of the world with a unified goal to cut down on greenhouse gases  
96 promoting climate change. These agreements, however, also led to an increased  
97 attention on the emissions from the combustion engines, since automotive sector  
98 accounts for around 25% of carbon emissions. To address these implicit demands  
99 placed on automotive industries, many new technologies came to forefront  
100 including gasoline and diesel direct injection technologies. Although these engine  
101 technologies are significantly fuel efficient than conventional engines and facilitate  
102 tremendous control of emissions with high power density, major economies around  
103 the world still felt the need to take more aggressive steps toward curbing the carbon  
104 emissions from the vehicular operation. It eventually led to various announcements  
105 during 2016–2018 by many countries including the United Kingdom, China, India,  
106 parts of Europe etc. to move away from new sales of passenger vehicles powered by

107 pure internal combustion engine in 2030–2040 timeframe. However, the nature of  
 108 technology to replace internal combustion engines on such a large scale is still  
 109 under debate. In the most likely scenario, it seems that the combustion engines will  
 110 stay for longer than hyped in the popular media, especially in the heavy-duty road  
 111 transport, marine and aviation sectors; however, to address the stricter regulations,  
 112 combustion engines must reinvent themselves.

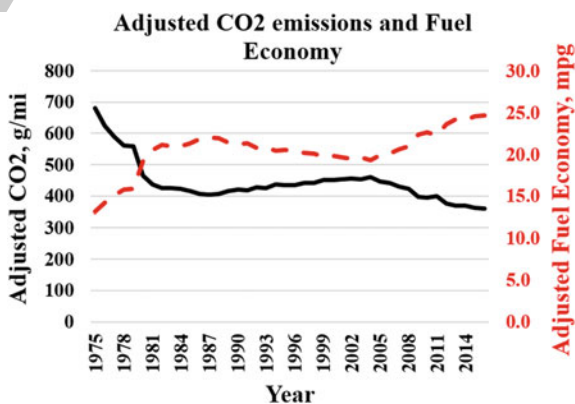
113 In this chapter, first, the regulatory framework around the world and their  
 114 potential directions in response to climate change, including road transport, marine,  
 115 and aviation sectors are discussed. In Sects. 2.3 and 2.4, the focus is shifted to fuel  
 116 and engine technologies in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

## 122 2.2 The Regulatory Framework

### 123 2.2.1 Fuel Economy and CO<sub>2</sub> Emission Standards 124 for Road Transport

125 As a response to climate change, increasing fuel import bills, energy security, and  
 126 wider impacts of transportation sector on the environment, the regulatory frame-  
 127 work across the world to improve the fuel economy and reduce the CO<sub>2</sub> emissions  
 128 has evolved over the past 50 years and has become quite stringent. Figure 2.1  
 129 shows the improvements in CO<sub>2</sub> emissions and fuel economy over the years for  
 130 passenger cars and light trucks (including pickup trucks, minivans, and SUVs) in  
 131 the US market. Between 2004 and 2016, the CO<sub>2</sub> emissions and fuel economy have  
 132 improved by 22 and 28%, respectively (EPA 2017). The data used here is from the

**Fig. 2.1** Historic CO<sub>2</sub> emissions reduction and fuel economy improvement in the US for passenger cars and light trucks (EPA 2017)



US Environment Protection Agency (EPA)'s adjusted results to better reflect on real-world emissions and fuel economy. The benefits of such 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<sub>2</sub> reduction of 16% in the 2010–2015 period (Agency EE 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<sub>2</sub> 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<sub>2</sub> emissions of passenger cars and light trucks in the US (Transport UDo 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 EPA sets the CO<sub>2</sub> standards since 2007, both standards are harmonized since 2010 for the cars and light-duty trucks of the model year 2012 and beyond.

**Table 2.1** Fuel economy and CO<sub>2</sub> emissions of passenger cars and light trucks in the US (Transport UDo 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 <sub>2</sub> emissions (in year)
US	Cars	36.2 mpg and 225 gCO <sub>2</sub> /mi (2016)
		55.3 mpg and 143 gCO <sub>2</sub> /mi (2025)
	Light trucks	28.8 mpg and 298 gCO <sub>2</sub> /mi (2016)
		39.3 mpg and 204 gCO <sub>2</sub> /mi (2025)
EU	Cars	130 gCO <sub>2</sub> /km (2015)
		95 gCO <sub>2</sub> /km (2021)
		30% CO <sub>2</sub> reduction compared to 2021 (2030)
	Vans	175 gCO <sub>2</sub> /km (2017)
		147 gCO <sub>2</sub> /km (2020)
30% CO <sub>2</sub> 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 <sub>2</sub> /km (2017)
	Light trucks	113 gCO <sub>2</sub> /km (2022)
		–

153 The EU legislation sets EU-wide CO<sub>2</sub> emission targets for new cars and commercial  
154 vehicles (vans) sold in the EU market. Similar government bodies set the fuel  
155 economy and/or CO<sub>2</sub> emissions standards in China, India, and in rest of the world.  
156 However, there are some differences in the interpretation of these regulations. First,  
157 vehicles are categorized differently in different regions; the maximum Gross  
158 Vehicle Weight (GVW) for passenger cars and light-duty trucks in the US is  
159 3856 kg, whereas that in the EU, China, and India is 3500 kg (Yang and  
160 Bandivadekar 2017). Also, the test cycles used for reporting and certifying these  
161 regulations are different. The US regulators use US combined cycle, while the EU,  
162 China, and India use New European Driving Cycle (NEDC). EU plans to shift to a  
163 worldwide harmonized Light vehicle Test Procedure (WLTP) in the future (Yang  
164 and Bandivadekar 2017). Therefore, direct comparison of these standards across  
165 various regions should be reported cautiously. However, across the globe, such  
166 standards are becoming ever stringent and the CO<sub>2</sub> emissions in most regions are  
167 expected to reduce by around 50% by 2025 compared to baseline years (baseline  
168 year is different for different regions, see Table 2.1) (Yang and Bandivadekar  
169 2017). Hence, it could be stated that such regulations are successful in reducing the  
170 global warming impact of the transportation sector and also bear financial benefits  
171 to the consumers and governments.

172 The fuel economy and CO<sub>2</sub> emission standards for the Heavy-Duty Vehicles  
173 (HDVs) are still evolving compared to Light-Duty Vehicles (LDVs). The EU only  
174 recently (COM//284 (EU) 2018) presented proposals for regulating HDV CO<sub>2</sub>  
175 emissions. The EU proposals calls for 15 and 30% reduction in CO<sub>2</sub> emissions,  
176 compared to 2019 levels, by 2025 and 2030, respectively, whereas 2030 reduction  
177 targets are subjected to review in 2022. Moreover, the EU proposals target only  
178 large lorries to start with and plan to widen the regulatory coverage to other HDV's  
179 post 2022. In 2016, the US EPA and NHTSA jointly announced the fuel economy  
180 and CO<sub>2</sub> emissions phase-II standards for medium- and heavy-duty vehicles  
181 through the model year 2027 (Transport UDo 2016). These standards are  
182 performance-based and are expected to further improve fuel savings by 25%  
183 compared to terminal phase-I respective category baseline. They rely on available  
184 and futuristic technological improvements to achieve the targets with a neutral  
185 attitude toward different technologies. In China, the stage-II and stage-III standards  
186 for HDV fuel consumption are expected to improve the fuel economy by 15%  
187 compared to 2015 levels by 2021. Fuel consumption standards for HDVs are also  
188 planned to be regulated in phases in India starting in 2018 (phase-I effective from  
189 2018, phase-II effective from 2021) (Report I 2017). It is expected that the coverage  
190 of fuel economy and CO<sub>2</sub> emissions standards will continue to grow across the  
191 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), etc.). 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<sub>2</sub> Emitting Vehicles (LEVs) (below 50 gCO<sub>2</sub>/km) vehicles, and plans to incentivize automakers who surpass their share of ZEVs and LEVs

**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



(15% in 2025 and 30% in 2030) with less stringent CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions in the aviation sector. As a part of this mechanism, all aviation operators that emit more than 10,000 tons of CO<sub>2</sub> per year must report their CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>x</sub>, SO<sub>x</sub>, 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.

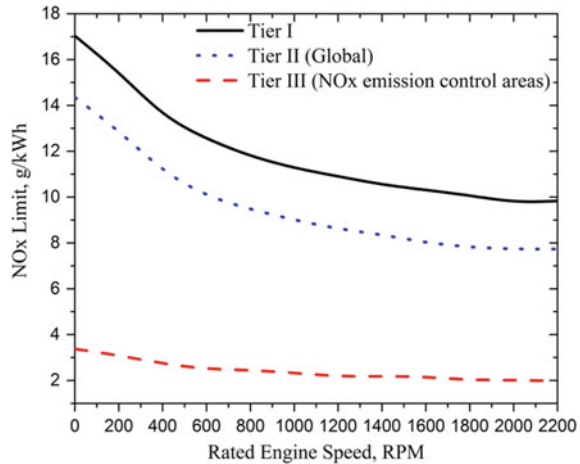
The MARPOL Annex VI (2010) also regulates the NO<sub>x</sub> emissions for seagoing vessels. The NO<sub>x</sub> emission levels are set for ships according to engine maximum operating speed levels and are different for old (Tier I, ships in service before January 1, 2000) and new (Tier II, ships constructed after January 1, 2011) vessels, and the vessels operating in NO<sub>x</sub>-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<sub>2</sub> footprint of the marine sector by 50% compared to 2008 levels by 2050. This CO<sub>2</sub> 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<sub>2</sub> 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<sub>x</sub> limit for different tiers as a function of engine speed (McGill and Winther 2013)



## 2.3 Developments in Transportation Sectors to Meet CO<sub>2</sub> 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<sub>2</sub> 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 (California 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<sub>2</sub> 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,

320 automotive manufacturers continue to invest in BEVs relying on future potential for  
321 improvement in batteries. Additionally, BEVs help the automotive manufacturers in  
322 meeting the fleet-averaged CO<sub>2</sub> emission regulations as they are considered as  
323 “Zero-Emissions Vehicles” under the current regulatory framework.

324 A more viable and practical option is to hybridize ICEs for improved fuel  
325 efficiency and reduced CO<sub>2</sub> emissions (Elgowainy et al. 2018). Different hybrid  
326 options may be suitable for a different class of vehicles within the light-duty sector  
327 and hence diversified options are expected moving forward. Series, parallel, and  
328 mix hybrid are the various options available currently and each has their own  
329 advantages and challenges. Series-hybrid vehicles offer a promising solution of  
330 increasing the fuel efficiency in urban driving conditions by allowing the engine to  
331 operate under its optimum condition. In such a scheme, ICE will continue to be the  
332 primary energy source for the vehicle.

333 Other options for reducing CO<sub>2</sub> emissions include using fuels with lower carbon  
334 to hydrogen ratio. In this case, CNG-driven vehicles become promising due to  
335 reduced CO<sub>2</sub> emissions by virtue of their low C/H ratio (Hesterberg et al. 2008).  
336 Long-term options include the use of Fuel Cell Vehicles (FCVs) powered by  
337 hydrogen or other fuels. Although FCVs have long been touted as the next trans-  
338 portation solution, their market uptake has been slow and they continue to be part of  
339 a niche market. However, some of the mainstream vehicle manufacturers are  
340 focusing again on fuel cell vehicles and have invested heavily in their research and  
341 development (Toyota 2018). The future of hydrogen produced from fossil sources  
342 using carbon capture and renewable hydrogen as a fuel, along with fast refueling  
343 and long driving range, makes it an attractive and eco-friendly solution. However,  
344 the high cost of fuel cell stack and the lack of hydrogen refueling infrastructure are  
345 significant bottlenecks currently. Economies of scale are expected to reduce the  
346 price of FCVs, however, this is a typical chicken and egg problem. Following  
347 Tesla’s lead, Toyota has also shared patents related to various aspects of FCV  
348 development to accelerate the growth in this segment (Toyota 2018). Additionally,  
349 three major Japanese automakers namely Toyota, Honda, and Nissan are cooper-  
350 ating to jointly accelerate the introduction of a hydrogen fueling network by sup-  
351 porting the operation cost and their development.

352 All the aforementioned medium to long-term options require the development of  
353 new fueling infrastructure and/or vehicle modifications and are, therefore,  
354 time-consuming and costly to implement. To summarize, there are multiple  
355 promising options to achieve future emission targets. However, a holistic cradle to  
356 grave analysis needs to be conducted to select an appropriate solution on a  
357 case-by-case basis rather than implementing a solution, which merely shifts the  
358 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 (Diesel 2013; Stanton 2010; Gible 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<sub>2</sub> 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<sub>2</sub> emissions (European Commission 2017) and the targets have been announced in 2018. AEA-Ricardo (Rexeis and Kies 2011) and TIAX (Transportation TICoC 2011) reports described extensive research effort by major heavy-duty manufacturers such as Daimler (2017), 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

401 measures are taken continuously to reduce vehicle CO<sub>2</sub> emissions in addition to  
402 other developments such as aerodynamics, the increment of bio-component into the  
403 fuel blends and hybridization of drivetrains.

### 404 2.3.3 Recent Developments in Marine Sector

405 There are several proposed compliance options to meet the upcoming IMO regulations  
406 and aspirations. As far as the availability of 0.5% m/m Low Sulphur Fuel Oil (LSFO) to  
407 meet the IMO Sulphur cap is concerned, there have been conflicting reports on the  
408 availability of such fuel. A study (Delft 2016) on the availability of compliant LSFO by  
409 the IMO chartered CE-Delft reported that all refineries have the capability to supply  
410 sufficient quantities of marine fuels with a Sulphur content of 0.50% m/m or less and with  
411 a Sulphur content of 0.10% m/m or less to meet demand for these products, while also  
412 meeting demand for nonmarine fuels. On the other hand, Ensys and Navigistics sup-  
413 plemental marine fuel availability study (Navigistics Ea 2016) presented to IMO sug-  
414 gests that the global refining industry will lack sufficient capacity to fully respond to the  
415 IMO Sulphur cap resulting in the price increase of not only fuel oil but also distillates and  
416 sweeter (low Sulphur) crudes. It is expected that the traditional fuels compliance option  
417 will be a mix of distillates (MGO/MDO), LSFO, and their blends; based on the compli-  
418 ance option used, the price for IMO-compliant marine fuels would be significantly  
419 more than HFO causing an increase in freight tariffs and will eventually result in some  
420 degree of stress on world economy. LNG is proposed as an important alternative option  
421 to HFO and LSFO in the marine sector. It offers several advantages; using a gas (LNG)-  
422 only engine can reduce the SO<sub>x</sub> and soot emissions by almost 100% without further need  
423 of after-treatment with manageable NO<sub>x</sub> emissions. The CO<sub>2</sub> saving potential of LNG  
424 compared to HFO is high (5–30%) but methane slip issues currently reduce the total CO<sub>2</sub>  
425 savings (0–20%). Depending on the location, LNG is also price competitive to distillates  
426 (MGO/MDO) compliance option with a discount of around \$5/MMBtu (Studies TOIfE  
427 2018a). However, there is a severe infrastructure development barrier that the LNG  
428 markets need to overcome for any meaningful marine market penetration and LNG share  
429 in marine sector is expected to be around 5% by 2025 (WoodMackenzie 2018).

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

**Table 2.4** Estimated life cycle CO<sub>2</sub> emissions reduction and current supply and uptake availability of alternative and renewable fuels (adopted from ITF 2018)

Alternative and renewable fuels	CO <sub>2</sub> emissions reduction (%)	Current supply and uptake potential (% of total marine energy)
Advanced biofuels	25–100	15
LNG	0–20	1–5
Hydrogen	0–100	0
Ammonia	0–100	0
Methanol	25–100	0–1

Several alternative and renewable fuel options are receiving increased attention in the marine sector to meet the upcoming SO<sub>x</sub>, NO<sub>x</sub>, and CO<sub>2</sub> 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<sub>x</sub> emissions, manageable NO<sub>x</sub> 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<sub>2</sub> neutral. Table 2.4 shows some estimates on CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions of the ships and is expected to reduce the CO<sub>2</sub> 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<sub>2</sub> 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

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

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

## 498 2.4 Technology Trends of Internal Combustion Engines 499 Toward High Efficiency

500 For the light-duty (LD) passenger transport applications, spark-ignited (SI) engines  
501 are mainstream, except Europe, and there is a lot scope for improvements. The  
502 gaseous emissions such as hydrocarbon (HC), carbon monoxide (CO), and nitrogen

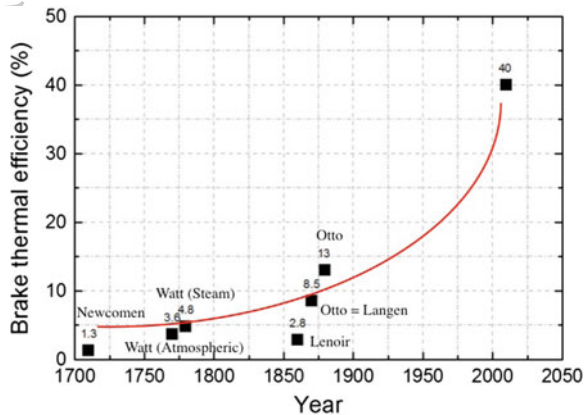


503 oxide ( $\text{NO}_x$ ) are treated by three-way catalytic converter with emissions levels  
 504 being already very low. Therefore, all research directions with SI engines are geared  
 505 toward the improvement of engine efficiency based on several strategies. The  
 506 commercial transport applications such as heavy-duty truck, and marine sector rely  
 507 on compression ignition (CI) engines. CI engine is more efficient than SI engines;  
 508 however, the emissions of  $\text{NO}_x$  and soot are higher, and diesel after-treatment is  
 509 quite expensive. The best possible way to mitigate these emissions would be  
 510 through in-cylinder phenomenon to achieve low-temperature combustion  
 511 (LTC) without compromising the efficiency. The other goals pertaining to CI engine  
 512 research are to maximize the engine efficiency by analyzing the thermodynamic  
 513 cycles and to develop a fuel-flexible hardware. The trends and recent developments  
 514 in this context are explained in the following sections.

### 515 2.4.1 High-Efficiency SI Engine Research

516 Ever since the advent of the combustion engine, the thermal efficiency of the ICE  
 517 has continuously improved. The evolution of efficiency over the past few centuries  
 518 is depicted in Fig. 2.3. The significant breakthrough came in 1876 from Nikolaus  
 519 August Otto, who pioneered the invention of an engine that is commonly referred to  
 520 as a gasoline engine. With the advancement in fuel supply system from the con-  
 521 ventional carburetor to port fuel injection (PFI) system, the efficiency improved to  
 522 35%. Subsequently, the transition from the PFI system to Gasoline Direction  
 523 Injection (GDI) system is marked as one of the technological milestones towards  
 524 higher efficiency in SI engine development (Zhao et al. 1999). The direct injection  
 525 of fuel into the cylinder with the GDI system reduces the global equivalence ratio,  
 526 and the cooling effect also adds to improvement in efficiency. In the wake of  
 527 various engine development strategies, the current efficiency of the SI engine has  
 528 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



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

#### 532 2.4.1.1 Engine Downsizing

533 Increasing the compression ratio of the SI engine and diluted combustion are  
534 important pathways to improve the efficiency of the engine. However, attaining a  
535 maximum compression ratio is limited by engine knock and dilution decreases the  
536 burnt rate of combustion. Engine downsizing is an effective approach to improve  
537 the efficiency that directly relates to the reduction of carbon footprint (Turner et al.  
538 2014). Despite the smaller displacement volume of the engine, the power output is  
539 higher through boosting that helps to induct more air to burn the fuel. Reducing the  
540 pumping, frictional and heat losses reduces the fuel consumption with the reduced  
541 engine out emissions (Avola et al. 2015). The pressure/temperature history of these  
542 modern engines are far away from the RON/MON conditions in that the octane  
543 rating scale is no longer agreeable. These engines depend on a factor “ $k$ ”, which is a  
544 constant in the octane index formulation ( $OI = RON - k * S$ ). The factor “ $k$ ” is  
545 negative for highly boosted downsized engines when knock limited and requires  
546 fuels with higher octane sensitivity (Avola et al. 2015). Variable Geometry Turbine  
547 (VGT) is a technological advancement in the development of turbocharged engines  
548 that allows for a fast transient response to synergize appropriately with the engine  
549 (Tang 2016). Currently, Mazda, Ford and Chevrolet, BMW, Mercedes-Benz, and  
550 Volkswagen Auto Group adopt downsized GDI engine with turbocharger tech-  
551 nology. The maximum efficiency of the reported commercial engine is 35% and  
552 efforts are being taken to further increase the efficiency. This advanced powertrain  
553 coupled with hybrid technology is beneficial and Toyota Prius plug-in hybrid  
554 electric vehicle showed a brake efficiency of 42%. Dilution through Exhaust Gas  
555 Recirculation (EGR) is an effective approach in a turbocharged GDI engine. Diluted  
556 combustion relates to stoichiometric operation in boosted downsized gasoline  
557 engines and offers greater potential to reduce fuel consumption (Wei et al. 2012).  
558 Cooled EGR reduces the engine knock, minimizes pumping losses and avoids the  
559 enrichment zones to improve fuel economy. However, the development of flame  
560 kernel under heavily diluted condition is difficult and high spark discharge system is  
561 recommended. Honda R&D recently demonstrated 45% efficiency using 35% EGR  
562 at an engine speed of 2000 rpm with an optimized combustion chamber design  
563 (Ikeya et al. 2015). In order to overcome the dilution tolerance and support  
564 auto-ignition; higher spark energy of 450 mJ is used. A 3% increase in efficiency  
565 when compared to the existing commercial vehicle is a promising improvement.  
566 When coupled with hybrid concept, the efficiency of this engine is expected to be  
567 the highest that has been conceived thus far.

### 2.4.1.2 Lean Burn Technology

Lean combustion in SI engines improves the fuel economy and reduces the global CO<sub>2</sub> 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 ( $\phi = 1$ ) 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) thorough 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 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 ( $S = \text{RON} - \text{MON}$ ), 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 imperative. The gasoline blended with the blend-stock is operated in a boosted SI engine to result 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 ( $\text{OI} = \text{RON} - k * S$ ). 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 developed. 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 optimum fuel-engine combination.

### 2.4.2 High-Efficiency CI Engine Research

Diffusion-controlled spray combustion leads to the formation of increased  $\text{NO}_x$  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  $\text{NO}_x$  and particulate matter emissions, whereas HC and CO emissions are decreased 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  $\text{NO}_x$  and PM. Measures to overcome this problem has been up-taken over several decades

650 and paved the way to the development of new combustion concepts. Instead of  
651 after-treatment technique, advanced combustion concepts such as Homogenized  
652 Charge Compression Ignition (HCCI) and Partially Premixed Combustion  
653 (PPC) are proposed for simultaneous reduction of  $\text{NO}_x$  and soot emissions (Zheng  
654 2009; Noehre et al. 2006). Furthermore, these combustion strategies also improve  
655 the efficiency due to low-temperature combustion (minimized heat loss), which  
656 mitigates the  $\text{CO}_2$  emission. Besides new combustion concepts, the thermodynamic  
657 cycle analysis to realize higher efficiency has been investigated and researched. The  
658 eight-stroke engine is the latest technology that improves the thermodynamic  
659 process to reduce the heat losses and allows for efficiency improvements. These  
660 renewed combustion concepts that aim to achieve 60% efficiency are current  
661 research initiatives pertaining to CI engine technology.

#### 662 2.4.2.1 High-Efficiency Combustion Concepts

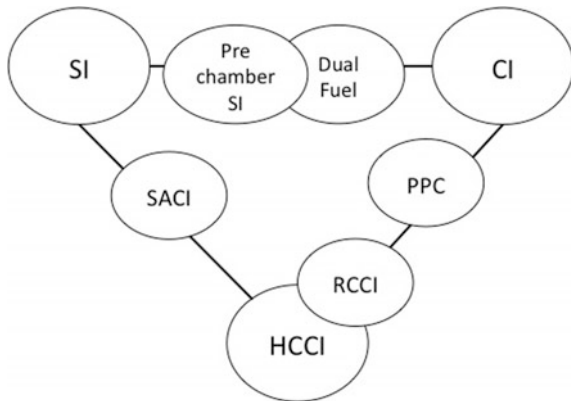
663 Few in-cylinder combustion strategies proposed to mitigate  $\text{NO}_x$  and soot emission  
664 without compromising engine efficiency including HCCI, PPC, and Reactivity-  
665 Controlled Compression Ignition (RCCI) (Sarangi 2012). These Low-Temperature  
666 Combustion (LTC) concepts reduce the local flame temperature and equivalence  
667 ratio in such a way that  $\text{NO}_x$  and soot formation are reduced simultaneously. When  
668 the Start of Injection (SOI) is advanced from late to early fuel injection timings,  
669 combustion drifts from CI toward HCCI condition (Vallinayagam et al. 2017).  
670 In HCCI mode, fuel and air are completely premixed during the significant delay  
671 period and combustion is controlled by mixture chemical kinetics. Given that the  
672 controllability of combustion is a problem at high load with HCCI due to rapid  
673 pressure rise rate; studies on PPC emerged that effectively controls combustion due  
674 to increased combustion stratification (Najafabadi 2017). While combustion phasing  
675 is sensitive to SOI in CI combustion, it is dependent on intake air temperature  
676 for HCCI combustion. PPC is intermediate between HCCI and CI combustion in  
677 that the fuel injection is crucial for controlling the combustion phasing. In 2001,  
678 Nissan Motor Company investigated diesel PPC through modulated kinetics  
679 combustion concept (Kimura et al. 2001). Based on EGR, the required ignition  
680 delay was created at various loading conditions. Due to low temperature and pre-  
681 mixed combustion, a simultaneous reduction in  $\text{NO}_x$  and soot emission was  
682 achieved. The high load diesel operation demanded 70% EGR, which deteriorated  
683 the combustion process. Given that diesel PPC was not advantageous at all the  
684 operating ranges, gasoline PPC was introduced in 2006 (Kalghatgi et al. 2006).  
685 When fuels with resistance to auto-ignition are used in CI engines, they create an  
686 adequate delay period for premixing; this decreases the in-cylinder temperature to  
687 suppress  $\text{NO}_x$  formation, while local fuel to air equivalence ratio is decreased to  
688 reduce soot emission. Gasoline PPC is also described as Gasoline Compression  
689 Ignition (GCI), which has grabbed more attention in the past decade and most of the  
690 engine manufacturers are in the endeavor to commercialize the first GCI engine  
691 (Perkins 2018).

692 Ignition assistance is required to support the auto-ignition and maintain com-  
693 bustion stability when using high RON gasoline fuel in a Compression Ignition  
694 (CI) engine. However, high RON fuels prove difficult to auto-ignite at low load  
695 condition, as the available boost is limited (Manente et al. 2009). In the current  
696 scenario, low-load GCI is a big challenge and efforts are being made to improve the  
697 combustion stability. Selection of low RON gasoline could avert this problem and  
698 RON 70 gasoline is an ideal candidate for GCI investigation (Solaka et al. 2012).  
699 Naphtha (a low octane gasoline fuel with RON  $\sim$  60–70) has been tested as a  
700 suitable fuel for GCI engines (Alabbad et al. 2018; Leermakers et al. 2013) due to  
701 its suitable fuel properties such as its optimal reactivity to ignite under compression,  
702 low well-to-tank carbon footprint due to reduced refinery processing and higher  
703  $H$  to  $C$  ratio (due to paraffinic composition) ascertaining lower tank-to-wheel carbon  
704 emissions. Furthermore, based on its boiling point (BP), naphtha can be categorized  
705 as light (BP = 75 °C) or heavy (BP = 175 °C). Since it is a less-processed fuel, less  
706 refining energy is required thereby reducing production costs; it is also less  
707 intensive in terms of reduced well-to-tank CO<sub>2</sub> emission. The vehicular demon-  
708 stration of naphtha in a PPC engine demonstrated improved fuel economy and  
709 better combustion stability at low load condition (Chang et al. 2013). Thus,  
710 low-load operation of GCI is possible without any auto-ignition problems using low  
711 RON gasoline or naphtha. However, the low RON gasoline fuels are not com-  
712 mercially available and adaption of these fuels could be a choice in the future. At  
713 present, high RON gasoline is being used commercially and strategies to overcome  
714 auto-ignition problems and enable low load and idle operation are essential. In this  
715 respect, Delphi is involved in the development of Gasoline Direct injection  
716 Compression Ignition (GDICI) engine using US market gasoline (Sellnau et al.  
717 2014, 2016). The fuel injection strategy was implemented in such a way to achieve  
718 PPC at very low fuel injection pressure, typical of GDI engines. Delphi electrical  
719 cam phaser's actuated the exhaust valve train to enable secondary valve lift,  
720 recuperating heat from hot exhaust gases to support auto-ignition at low loads.  
721 Retaining the residuals helps to reduce the oxygen flow rate and local flame tem-  
722 perature with increased heat capacity. The longer ignition delay also influences the  
723 local fuel to air equivalence ratio. As such, both NO<sub>x</sub> and soot emissions are  
724 simultaneously reduced, indicating low-temperature combustion. Measures to  
725 control the combustion by providing spark assistance provided a better solution  
726 (Manofsky et al. 2011). Spark-assisted GCI is the evolving technology toward the  
727 extension of low load limit until now (2018). A recent innovative combustion  
728 concept called Spark-Assisted Compression Ignition (SACI) of gasoline was  
729 introduced by MAZDA (2018). With Mazda's Skyactive-X is ready for launch on  
730 2019, it is touted as the world's first commercial gasoline engine running on  
731 compression ignition mode.

732 The pictorial layout in Fig. 2.4 elucidates the different high-efficiency com-  
733 bustion 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 (Studies TOIFE 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 (Studies TOIfE 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

804 number of kilometers are expected to be increased because of the ease of use  
805 offered by such models (Studies TOIfE 2018b). The profit margin and continuous  
806 vehicle availability are expected to be among major considerations of the vehicle/  
807 fleet operators under transportation as a service model, again, complete electrifi-  
808 cation of the LDV fleet in such a model could only be realized if the electric cars  
809 become price competitive and the charging times and the mileage of BEVs sig-  
810 nificantly improve. Fleet operators will also closely monitor all of these parameters  
811 for the scenarios where the government provided subsidies for electric vehicles and  
812 battery charging dry out.

813 In addition to the disruptions discussed above, some countries have announced  
814 their aspirations to ban ICE-only vehicles. Such aspirations are meant to curb the  
815 pollutants related to local air quality, the  $\text{NO}_x$ ,  $\text{SO}_x$ , CO, HCs and soot emissions,  
816 and the climate change. The governments of UK, France, China, India, Germany,  
817 along with city administrators of major metropolises including Paris, Barcelona,  
818 Madrid, have expressed aspirations to ban ICE only vehicles in 2030–2040 time-  
819 frame. Most of these aspirations are announced in the popular media without formal  
820 government-level proposals or regulations drafted thus far. Implicit in these news is  
821 the fact that most of these countries, although aspire to ban ICE-only vehicle, will  
822 still continue to use combustion engine hybridized in one form or another as a  
823 primary energy source for the vehicles. It is beyond question that transportation  
824 must do more to improve its environmental footprint. However, it is equally  
825 important that the governments and regulators, instead of picking the winners, take  
826 a balanced and informed approach while formulating policies and regulations for  
827 the transportation sector. Life Cycle Analysis (LCA)-based policies and  
828 decision-making (Abdul-Manan 2018) should be adopted to arrive at scientifically  
829 backed policies and practical solutions to improve the environmental impact of the  
830 transportation sector. All the technological options should be properly evaluated  
831 utilizing LCA-based methodologies to arrive at a sustainable transportation model  
832 for the future. Policy makers and regulators must avoid simple burden shifting as  
833 such short-sighted approaches may alleviate the pollution concerns in the cities but  
834 may not overcome the climate change concerns globally.

## 835 2.6 Conclusions

836 The mobility of man and goods accounts for around a quarter of greenhouse gas  
837 emissions globally and, therefore, naturally attracts the most stringent regulations  
838 for emissions and fuel efficiency. Here, current and prospective regulatory frame-  
839 work for road, marine, and aviation transport sectors, aimed at curbing the  $\text{CO}_2$   
840 emissions from the transportation is presented. It is shown that the fuel economy  
841 and  $\text{CO}_2$  emission targets are becoming stricter across the various transportation  
842 sectors. For light-duty sector, such regulations are even more stringent and the  
843 recent introduction of zero-emission mandates is forcing the OEMs to invest more  
844 in hybridization and electrification. The available compliance options for various

845 transport sectors are also discussed. Holistically speaking, the fossil fuel powered  
846 combustion engines/turbines are expected to continue powering the transport sector  
847 for decades to come. The passenger transport sector is expected to have a slow  
848 transition, spanning several decades, towards electrification. Several advanced  
849 engine technologies, with the potential to improve fuel economy and CO<sub>2</sub> emis-  
850 sions, including highly boosted and downsized SI engine concepts, pre-chamber SI  
851 engine concept, 8-stroke and GCI/PPC CI concepts are briefly discussed. Various  
852 disruption agents are presented, especially in the light-duty sector, and it is expected  
853 that the personal mobility models may change in the near future. Finally, it is  
854 argued that a LCA-based policy must be adopted for proposing any future regu-  
855 lations for the transport sector.

856 **Acknowledgements** The work reported was funded by Saudi Aramco under the FUELCOM  
857 program and by King Abdullah University of Science and Technology (KAUST) with competitive  
858 research funding given to the Clean Combustion Research Center (CCRC).

## 859 References

- 860 Abdul-Manan AF (2018) On the appropriate use of life-cycle thinking for evidence-based  
861 sustainable transport policy. *Environ Sci Policy Sustain Dev* 60:18–25
- 862 Agency EE (2018) Monitoring of CO<sub>2</sub> emissions from passenger cars—Regulation (EC) No 443/  
863 2009
- 864 Alabbad M, Issayev G, Badra J, Voice AK, Giri BR, Djebbi K, Ahmed A, Sarathy SM, Farooq A  
865 (2018) Autoignition of straight-run naphtha: a promising fuel for advanced compression  
866 ignition engines. *Combust Flame* 189:337–346
- 867 Alvarez CEC, Couto GE, Roso VR, Thiriet AB, Valle RM (2017) A review of prechamber ignition  
868 systems as lean combustion technology for SI engines. *Appl Therm Eng*
- 869 Attard WP, Toulson E, Huisjen A, Chen X, Zhu G (2012a) Spark Ignition and pre-chamber  
870 turbulent jet ignition combustion visualization. *SAE Technical Papers*
- 871 Attard WP, Blaxill H, Anderson EK, Litke P (2012b) Knock limit extension with a gasoline fueled  
872 pre-chamber jet igniter in a modern vehicle powertrain. *SAE Int J Engines* 5(3):1201–1215
- 873 Avola C, Copeland T, Duda R, Burke S, Akehurst CB (2015) Review of turbocharger mapping  
874 and 1D modeling inaccuracies with specific focus on two-stag systems. *SAE Technical Paper*  
875 Report No 0148–7191
- 876 Ayala FA, Heywood JB (2007) Lean SI engines: the role of combustion variability in defining lean  
877 limits. *SAE Technical Papers*
- 878 Bunce M, Blaxill H (2016) Sub-200 g/kWh BSFC on a light duty gasoline engine. *SAE Technical*  
879 *Paper*
- 880 CARB (2016) Zero-emission vehicle standards for 2018 and subsequent model year passenger  
881 cars, light-duty trucks, and medium-duty vehicles
- 882 Chang J, Kalghatgi G, Amer A, Adomeit P, Rohs H (2013) vehicle demonstration of naphtha fuel  
883 achieving both high efficiency and drivability with EURO6 engine-out NO<sub>x</sub> emission. *SAE*  
884 *Int J Engines* 6(1):101–119
- 885 COM//0767 final//0382 (COD) (2016) Proposal for a directive of the European parliament and of  
886 the council on the promotion of the use of energy from renewable sources (recast), COM//0767  
887 final//0382 (COD)
- 888 COM//284 (EU) (2015) Proposal for a regulation setting CO<sub>2</sub> emission performance standards for  
889 new heavy-duty vehicles

- 890 Cui H (2018) China's new energy vehicle mandate policy (Final Rule). Policy update.  
891 International Council on Clean Transportation, Washington, DC
- 892 Cummins K, Diesel CSU (2013) Program technology and system level demonstration of highly  
893 efficient and Class 8 trucks, presentation at of energy merit review
- 894 Daimler (2017) Daimler focus sustainability
- 895 De Groot GJ (1996) *Blighty: British society in the era of the great war*. Addison-Wesley Longman
- 896 Delft C (2016) Assessment of fuel oil availability, Final report Delft, July
- 897 Delgado O, Lutsey N (2014) The U.S. SuperTruck program: expediting development of advanced  
898 HDV efficiency technologies
- 899 Dutton K (2006) A brief history of the car, New Ideas. byronwinecom 1
- 900 Elgowainy A, Han J, Ward J, Joseck F, Gohlke D, Lindauer A, Ramsden T, Bidy M,  
901 Alexander M, Barnhart S, Sutherland I, Verduzco L, Wallington TJ (2018) Current and future  
902 united states light-duty vehicle pathways: cradle-to-grave lifecycle greenhouse gas emissions  
903 and economic assessment. *Environ Sci Technol* 52(4):2392–2399
- 904 EPA (2017) Carbon dioxide emissions and fuel economy trends report
- 905 European Commission (2017) Communication from the Commission to the European Parliament,  
906 the Council
- 907 Faria P, Marques P, Moura F, Freire J, Delgado AT, de Almeida R (2013) Impact of the electricity  
908 mix and use profile in the life-cycle assessment of electric vehicles. *Renew Sustain Energy Rev*  
909 24:271–287
- 910 Gibble K (2013) Scattering of cold-atom coherences by hot atoms: frequency shifts from  
911 background-gas collisions. *Phys Rev Lett* 110(18):180802
- 912 Gilroy RW (2016) SuperTruck II aims to more than double freight efficiency of Class 8s
- 913 Hanemann M (2008) California's new greenhouse gas laws. *Rev Environ Econ Policy* 2(1):  
914 114–129
- 915 Hawkins TR, Singh B, Majeau Bettez G, Strömman AH (2013) Comparative environmental life  
916 cycle assessment of conventional and electric vehicles. *J Ind Ecol* 17(1):53–64
- 917 Hebert A (2017) Developing future light-duty vehicle regulations in Resource Board, California
- 918 Hesterberg TW, Lapin CA, Bunn WB (2008) A comparison of emissions from vehicles fueled  
919 with diesel or compressed natural gas. *Environ Sci Technol* 42(17):6437–6445
- 920 Huo H, Cai H, Zhang Q, Liu F, He K (2015) Life-cycle assessment of greenhouse gas and air  
921 emissions of electric vehicles: a comparison between China and the U.S. *Atmos Environ*  
922 108:107–116
- 923 ICAO Resolution A39-2 (2016) Consolidated statement of continuing ICAO policies and practices  
924 related to environmental protection—climate change and global market-based measure  
925 (MBM) scheme, 39th ICAO Assembly
- 926 IEA (2017) Energy technology perspectives. <http://www.iea.org/etp/explore/>
- 927 Ikeya K, Takazawa M, Yamada T, Park S, Tagishi R (2015) Thermal efficiency enhancement of a  
928 gasoline engine. *SAE Int J Engines* 8
- 929 ITF (2018) Decarbonizing maritime transport: pathways to zero-carbon shipping by 2035. OECDs  
930 International Transport Forum (ITF)
- 931 Johnson TV (2010) Review of diesel emissions and control. *SAE Int J Fuels Lubr* 3:16–29
- 932 Kalghatgi G (2018) Is it really the end of internal combustion engines and petroleum in transport?  
933 *Appl Energy* 225:965–974
- 934 Kalghatgi GT, Risberg P, Ångström HE (2006) Advantages of fuels with high resistance to  
935 auto-ignition in late-injection, low-temperature, compression ignition combustion. SAE  
936 Technical Paper
- 937 Kimura K, Tsukahara K, Usui T, Okuda J, Kitamura Y, Kosuge M, Sano T, Tohyama S,  
938 Yamanaka O, Yoshii Y, Umemura S (2001) Low-dose tissue plasminogen activator followed  
939 by planned rescue angioplasty reduces time to reperfusion for acute myocardial infarction  
940 treated at community hospitals. *Jpn Circ J* 65(10):901–906
- 941 Kline SJ, Rosenberg N (2009) An overview of innovation
- 942 Lam N, Tuner M, Tunestal P, Andersson A, Lundgren S (2015) Double compression expansion  
943 engine concepts: a path to high efficiency. *SAE Int J Engines* 8



- 944 Leermakers CAJ, Bakker PC, Somers LMT, Goey L, Johansson BH (2013) Butanol-diesel blends  
945 for partially premixed combustion. SAE Int J Fuels Lubr 6(1):217–229
- 946 Lutsey N (2018) The ever-improving efficiency of the diesel engine. [https://www.theicct.org.](https://www.theicct.org/blogsstaffeverimprovingefficiencydieselengine)  
947 [blogsstaffeverimprovingefficiencydieselengine](https://www.theicct.org/blogsstaffeverimprovingefficiencydieselengine). Accessed 20 July
- 948 Manente V, Johansson B, Tunestal P, Cannella W (2009) Effects of different type of gasoline fuels  
949 on heavy duty partially premixed combustion. SAE Int J Engines 2(2):71–88
- 950 Manofsky L, Vavra J, Assanis DN, Babajimopoulos A (2011) Bridging the gap between HCCI and  
951 SI: spark-assisted compression ignition. SAE Technical Paper
- 952 Manzetti S, van der Spoel D (2015) Impact of sludge deposition on biodiversity. Ecotoxicology 24  
953 (9):1799–1814
- 954 MAZDA (2018) Next-generation Skyactive-X gasoline engine. MAZDA
- 955 McGill WR, Winther K (2013) Alternative fuels for marine applications, from the motor fuels  
956 implementing agreement. A report from the IEA advanced motor fuels implementing  
957 agreement 54
- 958 McNeil I (2002) An encyclopedia of the history of technology. Routledge
- 959 Melton N, Axsen J, Sperling D (2016) Moving beyond alternative fuel hype to decarbonize  
960 transportation. Nat Energy 1(3)
- 961 Mitchell J Jr, Dzerdzeevskii B, Flohn H, Hofmeyr W, Lamb H, Rao K, Wallen C, Mitchell  
962 Wallen J (1966) Climate change. World Meteorological Organisation Technical note
- 963 Morris I (2015) The unexpected origin of human values. New Sci 226(3017):28–31
- 964 Mulero E (2016) DOE debuts 2nd phase of SuperTruck; pledges \$80 million to efficiency effort.  
965 American Trucking Associations. ISSN: 0041–1558
- 966 Najafabadi MI (2017) Optical study of stratification for partially premixed combustion. TU/e  
967 Navigistics Ea (2016) Supplemental marine fuel availability study to the IMO
- 968 Noehre C, Andersson M, Johansson B, Hultqvist A (2006) Characterization of partially premixed  
969 combustion. SAE Technical Paper
- 970 Perkins C (2018) Mazda says its next-generation gasoline engine will run cleaner than an electric  
971 car. <http://www.roadandtrack.com>. [https://www.roadandtrack.com/new-cars/car-technology/  
972 a15912314/mazda-skyactiv-3-gas-clean-as-ev/](https://www.roadandtrack.com/new-cars/car-technology/a15912314/mazda-skyactiv-3-gas-clean-as-ev/)
- 973 Regulation (EU) No 253 (2014) European Parliament and of the Council amending Regulation  
974 (EU) No 510/ to define the modalities for reaching the target to reduce CO<sub>2</sub> emissions from  
975 new light commercial vehicles (2014)
- 976 Regulation (EU) No 333 (2014) European Parliament and of the Council of 11 March 2014  
977 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to  
978 reduce CO<sub>2</sub> emissions from new passenger cars
- 979 Report I (2017) Fuel consumption standards for heavy-duty vehicles in India
- 980 MARPOL Annex VI (2010) Revised Marpol Annex VI 176(58)
- 981 Rexeis A, Kies S, Hausberger M (2011) Reduction and testing of greenhouse gas emissions from  
982 heavy duty vehicles-LOT 2. Development and testing of a certification procedure for CO<sub>2</sub>  
983 emissions and fuel consumption of HDV
- 984 Sarangi A (2012) Diesel low temperature combustion: an experimental study. Loughboro  
985 University
- 986 Scania (2017) The Scania report
- 987 Sellnau M, Foster M, Hoyer K, Moore W, Sinnamon J (2014) Development of a gasoline direct  
988 injection compression ignition (GDICI) Engine. SAE Int J Engines 7(2):835–851
- 989 Sellnau M, Foster W, Moore J, Sinnamon K, Hoyer W, Klemm M (2016) Second generation  
990 GDICI multi-cylinder engine for high fuel efficiency and US tier 3 emissions. SAE Int J Engines  
991 9:1002–1020
- 992 Seyferth D (2003) The rise and fall of tetraethyllead. 1. Discovery and slow development in  
993 european universities, 1853–1920. Organometallics 23(5):2346–2357
- 994 Shah A, Tunestal P, Johansson B (2012) Investigation of performance and emission characteristics  
995 of a heavy duty natural gas engine operated with pre-chamber spark plug and dilution with  
996 excess air and EGR. SAE Int J Engines 5(4):1790–1801

- 997 Shankar VSB, Lam N, Andersson A, Johansson B (2017) Optimum heat release rates for a double  
998 compression expansion (DCEE) engine. SAE Technical Paper
- 999 Shankar B, Shankar V, Johansson B, Andersson A (2018) Double compression expansion engine:  
1000 a parametric study on a high-efficiency engine concept. SAE Technical Paper Series
- 1001 Solaka SA, Boshamer SE, Parworth CL, Heard GL, Setser DW, Holmes BE (2012) Isomerisation  
1002 of CF<sub>2</sub>CICH<sub>2</sub>Cl and CFCI<sub>2</sub>CH<sub>2</sub>F by interchange of Cl and F atoms with analysis of the  
1003 unimolecular reactions of both molecules. Chemphyschem Eur J Chem Phys Phys Chem 13  
1004 (3):869–878
- 1005 Splitter DA, Pawlowski A, Wagner R (2016) A historical analysis of the co-evolution of gasoline  
1006 octane number and spark-ignition engines. Front Mech Eng 1
- 1007 Sripad S, Viswanathan V (2017) Performance metrics required of next-generation batteries to  
1008 make a practical electric semi truck. ACS Lett 2:1669–1673
- 1009 Stanton D (2010) High efficient clean combustion for SuperTruck. DEER 2010
- 1010 Studies TOIFE (2018a) A review of demand prospects for LNG as a marine transport fuel
- 1011 Studies TOIFE (2018b) Disruptive change in transport sector. The Oxford Institute for Energy  
1012 Studies, p 112
- 1013 Tang H (2016) Application of variable geometry turbine on gasoline engines and the optimisation  
1014 of transient behaviours
- 1015 Thiel C, Schmidt J, Zyl AV, Schmid E (2014) Cost and well-to-wheel implications of the vehicle  
1016 fleet CO<sub>2</sub> emission regulation in the European Union. Transp Res Part A 63(4):25–42
- 1017 Toulson E, Schock HJ, Attard WP (2010) A review of pre-chamber initiated jet ignition  
1018 combustion systems. SAE Technical Paper
- 1019 Toyota C (2018) New vehicle zero CO<sub>2</sub> emissions
- 1020 Transport UDo (2012) 2017–2025 model year light-duty vehicle greenhouse gas emissions and  
1021 corporate average fuel economy standards
- 1022 Transport UDo (2016) Greenhouse gas emissions and fuel efficiency standards for medium- and  
1023 heavy-duty engines and vehicles—phase 2
- 1024 Transportation TICoC (2011) European union greenhouse gas reduction potential for heavy-duty  
1025 vehicles
- 1026 Tully L (2002) A universal view of data. Interview by Anne Zender. J AHIMA 73(10):92
- 1027 Turner JWG, Popplewell A, Richardson S, Lewis AGJ, Akehurst S (2014) Ultra boost for  
1028 economy: realizing a 60% downsized engine concept. SAE Int J Engines 7:387–417
- 1029 Tushman ML (1997) Winning through innovation. Strat Leadship 25(4):14–19
- 1030 UNFCC (1992) United Nations framework convention on climate change. United Nations  
1031 New York
- 1032 UNFCC (2015) United nations framework convention on climate change, Paris, France
- 1033 U.S. DOE (2016) Co-optimization of fuels & engines. Bioenergy
- 1034 Vallinayagam R, Vedharaj S, An Y, Dawood A, Najafabadi MI, Somers B, Johansson B (2017)  
1035 Combustion stratification for naphtha from CI combustion to PPC. SAE Technical Paper
- 1036 Wayne A (1970) A.M. Association. Automobiles of University Press
- 1037 Wei H, Zhu T, Shu G, Tan L, Wang Y (2012) Gasoline engine exhaust gas recirculation—a  
1038 review. Appl Energy 99(2):534–544
- 1039 WoodMackenzie (2018) IMO 2020 updated analysis of the marine fuel sulphur changes. [https://  
1040 www.woodmac.com/reports/refining-and-oil-products-imo-2020-updated-analysis-of-the-  
1041 marine-fuel-sulphur-changes-18902](https://www.woodmac.com/reports/refining-and-oil-products-imo-2020-updated-analysis-of-the-marine-fuel-sulphur-changes-18902)
- 1042 Yang Z, Bandivadekar A (2017) Light-duty vehicle greenhouse gas and fuel economy standards.  
1043 ICCT report
- 1044 Yao Z, Zheng HML (2009) Progress and recent trends in homogeneous charge compression  
1045 ignition (HCCI) engines. Prog Energy Combust Sci 35:398–437
- 1046 Zhao F, Lai MC, Harrington DL (1999) Automotive spark-ignited direct-injection gasoline  
1047 engines. Prog Energy Combust Sci 25:437–562

# Author Query Form

Book ID : **472069\_1\_En**

Chapter No : **2**

Please ensure you fill out your response to the queries raised below and return this form along with your corrections.

Dear Author,

During the process of typesetting your chapter, the following queries have arisen. Please check your typeset proof carefully against the queries listed below and mark the necessary changes either directly on the proof/online grid or in the 'Author's response' area provided below

Query Refs.	Details Required	Author's Response
AQ1	Please check and confirm if the author names and initials are correct.	
AQ2	Please approve the edit made in the chapter title.	
AQ3	Please provide complete detail for references 'MARPOL Annex VI (2010), Daimler (2017), Scania (2017)'.	