Road Vehicle Technologies and Fuels

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ABSTRACT

Road vehicles are an indispensable part of human daily lives. Compression and spark ignition powertrains have been continuously evolving towards more efficient and cleaner technologies. The social awareness of the impact on the environment and human health of the toxic pollutants emitted during the combustion of fossil fuels has led to the introduction of legislation that restricts the emission limits of road vehicles. Vehicle manufacturers are researching and rapidly developing technologies that can offer both reduced fuel consumption and low emission of nitrogen oxides (NO_x), particulate matter (PM), carbon dioxide, carbon monoxide and unburnt hydrocarbons. This chapter provides an overview of the basic road vehicle transportation concepts from the past to the future trends, from the development of the precise fuel injection systems to recent research in new near-zero NO_x-PM emission combustion modes. Apart from the engine itself, alternative fuels can have benefits in pollution depletion. Bioalcohols, liquefied petroleum gas, compressed natural gas or hydrogen for spark ignition engines and fatty acid methyl esters or hydrotreated vegetable oil for diesel engines are under research. The benefits and barriers of these alternative fuels have been discussed. The inherent trade-off between pollutants and high-efficiency engines and the use of after-treatment systems to reduce engine-out emissions are also explored. The current state of the market share as well as a forecast for the near future are also parts of this chapter.

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1 Background

Energy demand is forecast to increase by a third by 2040, as reported in the World Energy Outlook by the International Energy Agency in 2015.[1,2] Currently, energy demand is primarily fulfilled by fossil fuels (86% of the total energy required for the global demand[3] in 2014), despite the considerable efforts in promoting the use of renewable energy sources. The increment in the global energy demand is mainly driven by countries that are not members of the Organisation for Economic Co-operation and Development. Therefore, it is expected that fossil fuels are going to continue to play a significant role in the worldwide energy sector.

The transportation sector has a considerable impact on fuel security, as well as on quality of life.[4] Ischaemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease and acute lower respiratory tract infection caused by ambient air pollution represented 6.7% of all deaths in 2012.[4] Therefore, concerns regarding energy security and the adverse impact on climate change and air quality have motivated regulatory bodies to impose increasingly strict emission limits and the methodologies to quantify them. Currently, vehicle emission and performance evaluation procedures are required to be carried out in a laboratory-controlled environment using a chassis dynamometer. The vehicle emission limits and procedures are dependent on the type of vehicle and geographical region. In Europe, the new European driving cycle is currently being used for this purpose, while in the USA, driving cycles such as FTP7 or US06 are those that are used for emission standards. The above cycles will be replaced by the worldwide harmonised light vehicles test procedure (WLTP) in order to reduce the gap between official and real-word emissions.[5] In Europe, this will be implemented in 2017. There is some scepticism regarding whether the WLTP will actually represent real emissions, and therefore the real driving emissions (RDE) test is planned to be imposed between 2017 and 2021. Instead of laboratory testing, in the RDE, emissions will be analysed using portable emissions measurement systems.[5]

The impact of the transportation sector on the environment and fuel security depends on the vehicle, driver behaviour and transport and mobility patterns. From a vehicular point of view, the materials used to build the vehicle (light weighting), the strategies introduced for enhancing the handling and riding of the vehicle and the energy conversion systems (the main scope of this chapter) are the main factors that affect fuel economy and exhaust emissions. Original equipment manufacturers are offering an enormous selection of vehicle types, modular vehicle configurations and endless energy and emission management strategies to fulfil the needs and requirements of society. Road vehicles are classified based on their application, propulsion system and energy supply/fuel type.

(i) Application: different vehicle categories are adopted depending on the geographical region, weight of the vehicle, number of passengers, utilisation and specific regulation. In road vehicles, two main groups are defined: light and heavy duty.

(ii) Propulsion system: conventional: spark ignition (SI) and compression ignition (CI); hybrid not off-vehicle charging: micro, mild and full-hybrid; hybrid off-vehicle charging: plug-in hybrid and range extender; pure electric vehicle (e-vehicle).

(iii) Energy supply/fuel type: crude oil: gasoline, diesel, natural gas, liquefied petroleum gas (LPG); bio-ethanol; biodiesel; hydrogen; synthetic fuels; power station/power grid.

In this chapter, a review of the current engine technologies in addition to the future trends in the automotive sector is performed, as well as the main alternative fuels that have been researched.

1.1 Fuels and Pollutants Emitted

The current road vehicle fleet is powered predominantly by fossil fuels, with a small proportion being electric vehicles. The main fossil fuels in use are gasoline (petrol), comprising mostly aliphatic and aromatic hydrocarbons (HCs), and diesel, which contains a less volatile mixture of HCs. Alcohols may be blended into gasoline and biodiesel into diesel fuel. Also in use are LPG—mainly propane and butane, and liquefied natural gas (LNG) or compressed natural gas (CNG)—composed mostly of methane.

Atmospheric emissions include the following:

(i) Unburned fuel, derived from evaporation, leakage or inadequate combustion.

(ii) Major combustion gases, carbon dioxide and water vapour:

$$e.g.\ C_8H_{18} + 12.5O_2 \rightarrow 8CO_2 + 9H_2O.$$

(iii) Minor combustion gases; these include products of incomplete combustion (*e.g.* carbon monoxide) and partial oxidation of HCs (*e.g.* aldehydes and ketones). Benzene derives from both unburned fuel and thermal breakdown of other aromatic compounds.

(iv) Compounds synthesised at high temperatures such as nitric oxide (a major component of NO_x) whose main source is from combustion of atmospheric nitrogen and oxygen in the engine:

$$N_2 + O_2 \rightarrow 2NO.$$

(v) Particulate matter (PM), generally measured in the atmosphere as $PM_{2.5}$ and PM_{10}, which is formed from HC fuels in the combustion process.

The emissions of greenhouse gases (carbon dioxide, methane and nitrous oxide) are considered in Chapter 2, and toxic, locally acting air pollutants are discussed in Chapter 3.

2 Compression Ignition Engines

In a CI engine, the fuel–air mixture is auto-ignited due to high temperatures and pressures in the combustion chamber. They have inherently higher thermal efficiencies with respect to their counterpart SI engines due to their higher compression (increased thermodynamic efficiency) and expansion ratios (minimised waste thermal energy discharged to the exhaust[6,7]), less pumping losses (there is no need for a throttle to regulate the load) and closer operation to the ideal cycle.[8] Technological improvements such as the use of high-pressure common rail direct injection (DI) systems and advanced forced induction techniques (*e.g.* variable geometry turbochargers) have raised the demand for CI engines also in light duty vehicles, particularly in Europe. Common rail injection systems overcome some of the limitations of older injection technologies as they enable both high fuel injection pressures and multiple fuel injections at low engine speeds in order to facilitate improved fuel atomisation, vaporisation and fuel–air mixing. Forced air induction allows a larger mass of fuel to be burnt, producing more power for the same size engine or enabling engine downsizing (high power-to-weight ratio). Variable-geometry turbocharger systems offer the possibility to recover part of the waste energy present in the exhaust gas, as well as simultaneously producing low speed boost and low end torque,[6] reducing pumping and friction losses at part-load operation and improving fuel economy and CO_2 emissions overall.

However, conventional CI engines emit higher levels of particles and oxides of nitrogen (NO_x) emissions compared to conventional SI engines. The presence of local rich-in-fuel heterogeneous air–fuel regions (due to the short time available for air–fuel mixing[7]) and the locally high flame temperature are responsible for the formation of soot or PM. Those high flame temperatures and the presence of oxygen and nitrogen are also responsible for NO_x emission formation. Exhaust gas recirculation (EGR) has been applied as a strategy to control NO_x emissions, reducing the oxygen availability in the combustion chamber (dilution effect) as well as increasing the overall heat capacity of the cylinder by adding CO_2, water vapour (H_2O) and N_2, which reduces the local flame temperature (thermal effect) and thus NO_x formation.[9] Although, EGR is effective at reducing NO_x formation, it also increases soot formation (PM–NO_x trade-off) as a result of the reduced oxygen availability in the combustion chamber (dilution effect).[10] Therefore, simultaneous reductions of particles and NO_x emissions in the engine cylinder when applying conventional combustion strategies (*e.g.* multiple injections, forced induction and EGR) have been always a challenge due to the well-known NO_x–particulate emissions trade-off.[11] This trade-off has motivated the search for cleaner fuels as well as exhaust gas after-treatment technologies to meet the increasingly strict emission regulations. An overview of the transformation of the diesel engine technologies to control pollutants as a consequence of the European legislation is presented in Figure 1.[12]

A combination of different catalysts (after-treatment systems) is required for the simultaneous removal of the pollutants. Diesel oxidation catalysts (DOCs)

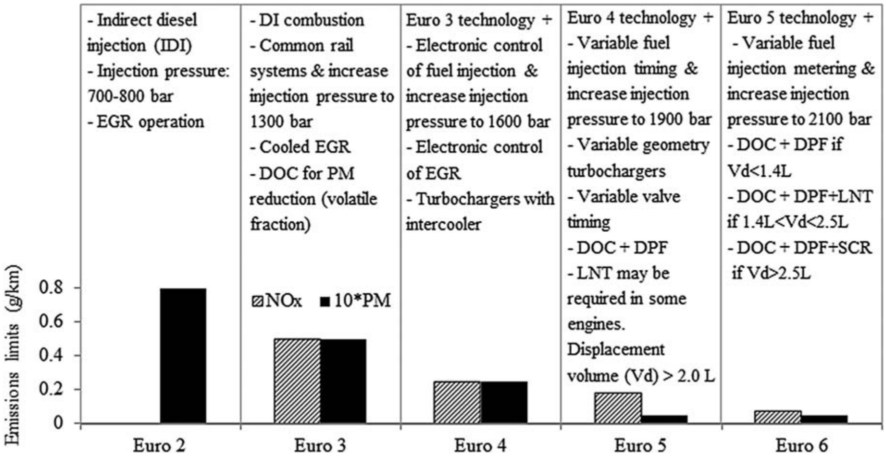

Figure 1 Diesel technology evolution as a consequence of European legislation. Adapted with permission from ref. 12.

are commonly used to oxidise CO, gas-phase HCs and the organic fraction of diesel particles to CO_2 and H_2O. Additionally, the oxidation of NO to NO_2 (which has been reported to facilitate passive diesel particle filter [DPF] regeneration and the performance of some selective catalytic reduction [SCR] catalysts) also occurs over the DOC. DPFs are used for the control of particle emissions together with a combined strategy of engine modification (*e.g.* high-pressure pumps, increased number of smaller injector nozzles and multiple injections).[13] Although this has been successfully introduced, energy-efficient and controlled filter regeneration methods are still being developed in order to maintain their long-term operation. NO_x emission abatement during lean exhaust conditions is much more difficult than in SI engines, especially under low exhaust gas temperatures. Currently, the legislative NO_x emissions of diesel vehicles have been met through engine control methods alone. However, with future legislation limits becoming more stringent, after-treatment NO_x control methods are recommended. There are two distinct approaches being developed. These include NO_x-SCR to N_2 with ammonia (NH_3-SCR) or HC (HC-SCR) and NO_x trapping with periodic reductive regeneration (lean NO_x trap/NO_x adsorber catalysts). In addition, advanced in-cylinder abatement techniques that rely on a combustion process at relatively low local temperatures and the absence of heterogeneous local rich-in-fuel air–fuel regions are also being researched and discussed (low-temperature combustion).

3 Spark Ignition Engines

Since the inception of the first SI engine more than a century ago, gasoline technology has witnessed several transformations towards better efficiency and lower emissions. Unburnt HCs, carbon monoxide and nitrogen oxide have traditionally been the problematic emissions of SI engines. Three-way catalysts (TWCs) have been used since the 1970s as the only after-treatment device for gasoline,[14] as they are capable of simultaneously controlling total hydrocarbons (THCs), CO and nitrogen oxides with efficiencies up to 99% by limiting the presence of oxygen in the exhaust stream under stoichiometric engine operation. Therefore, any technological advance in SI engines has always been influenced by the presence of the TWC. Probably one of the most notable examples of gasoline development is the evolution of the fuel delivery system.[15] Carburettors were the main fuel delivery systems in the late 1970s and early 1980s.[15] However, with carburettors, as the air/fuel ratio was not maintained at close to stoichiometric levels, the use of a TWC for emission control was not viable.[16] In the early 1980s, carburettors were replaced with the first fuel injection system,[15] throttle body injection, which became widespread between 1990 and 2005, particularly for trucks.[15] However, there were still issues associated with slower transport of fuel than air from the upstream of the throttle plate to the cylinder.[6] Between 2000 and 2015, the fuel delivery system started changing to port fuel injection (PFI). In PFI, the fuel is injected in the intake manifold and the fuel quantity is more accurately controlled per cylinder and per the amount of air needed.[6] The required air/fuel ratio for efficient TWC operation was maintained close to stoichiometric levels using a lambda sensor in the engine exhaust. The advantages of PFI over carburettors are the higher achievable engine volumetric efficiency that leads to increased power and torque output, more uniform fuel distribution, precise control of lambda during cold start and engine warm-up, fuel quantity being controlled per cylinder, more rapid engine response to throttle position changes and lower noise.[6,16] Despite these improvements, PFI engines cannot meet the current targets for CO_2 emissions (130 $\mathrm{g\,km^{-1}}$ in 2015 and 95 $\mathrm{g\,km^{-1}}$ by 2020) and the stricter pollutant emission legislation.[8,16] In the early 1990s, gasoline DI (GDI) engines were successfully developed and started replacing PFI systems.[15] The first engine produced using DI was developed by Mitsubishi in 1996.[17]

GDI engines usually operate at stoichiometric conditions near full load with early injection in the admission stroke to obtain a homogeneous air/fuel ratio in the whole combustion chamber. At part and low engine loads, the fuel injection timing could be delayed to the compression stroke; this enables the mixture to be stratified and for there to be a rich-in-fuel region close to the spark plug to start the combustion, but the global mixture is lean (*i.e.* the combustion occurs with air excess).[8,17] Lean air/fuel mixtures burn more slowly and at lower pressure and temperature peaks than stoichiometric combustion, leading to reduced knock tendency (a characteristic noise produced in SI engines when the end-gas auto-ignites, producing high-pressure waves that can damage the piston) and allowing increased compression ratios.[8] GDI advantages are reduced fuel consumption and thus lower tank-to-wheel CO_2 emissions. Injecting the fuel directly into the combustion chamber improves the accuracy of the fuel quantity and therefore the control of air/fuel ratios during dynamics. The charge cooling increases the volumetric efficiency and reduces knock probability, allowing for an increase in the compression ratio. Other advantages are the reduced throttle losses of the gas exchange, higher thermal efficiency due to the possibility of stratified operation, lower heat losses, rapid starting, better cold start performance and drive control.[16–18] Depending on the air–fuel mixture preparation, GDI engines can be classified as wall guided, air guided or spray guided. These three follow different approaches to achieve the same objective: create an ignitable mixture before the spark event. Wall- and air-guided systems are considered the first-generation GDI engines. In wall-guided engines, the fuel is directed towards a specially shaped piston bowl that moves the flow to the spark plug. This system has several inefficiencies derived from the fuel impingement in the piston resulting in fuel consumption, CO, unburnt HCs and soot penalties. In air-guided systems, the air flow is in charge of moving the fuel to the spark plug. The fuel impingement in the piston is avoided and thus soot formation does not occur. However, this system is highly dependent on air motion and suffers from high cycle-by-cycle variations. Spray-guided systems are known as the second-generation GDI engines. In these cases, the fuel is injected near the spark plug and the injector is located between the intake and exhaust valves contrary to wall- and air-guided systems in which the injector is side mounted. The advantages of spray-guided systems are the reduced wall wetting, the performance at part and full loads being optimised simultaneously, the increased stratified range, the reduced sensitivity to cylinder-by-cylinder variations, the reduction in HCs and the better fuel economy. However, the harsher in-cylinder conditions promote the fouling of the spark plug and injectors, which can deteriorate combustion stability.[16,17,19] GDI engines can be also coupled with other technologies, such as turbocharging, downsizing and variable valve timing (VVT), which can further exploit the potential of DI to achieve higher efficiencies and further fuel economy improvements. For instance, engine downsizing shifts the engine operation to wide open throttle, avoiding the least efficient part load operation of SI engines and so improving fuel economy.[17] Furthermore, the reduced surface area lowers friction losses and the smaller engine decreases vehicle weight.[17] It has been reported that fuel consumption reductions of between 12.1% and 24.6% can be achieved.[20] The challenge associated with downsizing is combustion limitation, as these engines are more prone to knock, reducing the efficiency and transient operation.[21] The term ‘rightsizing’ is currently used by automotive manufacturers and is defined as the optimum combination of displacement, power and torque delivery, fuel consumption and operating characteristics for a given application.[22]

Despite the potential of GDI engines, the main drawbacks are the increased level of PM compared to PFI and injector deposit formation.[17,23–25] While injector deposits are detrimental for the fuel spray pattern and for the engine’s efficiency, PM is known to be a toxic pollutant and any potential increase raises concerns about health effects. PM is formed from a carbonaceous core known as soot onto which HCs, including polyaromatic HCs, are adsorbed. PM has been classified by the International Agency for Research on Cancer as carcinogenic to humans,[26] and there are several respiratory and cardiovascular exacerbations related to its inhalation.[27] In addition, soot is a contributor to global warming.[28] For all of the above reasons, GDI vehicles have been included in the upcoming legislation to limit the particle number emitted. This is the case of the Euro 6c, in which the particle number limit is established at 6×10^{11} particles kg^{-1}.[29] Although some authors claim that with the optimisation of engine parameters this limit can be met,[30] others suggest that the introduction of gasoline particulate filters will be necessary to meet more stringent legislation.[31] Furthermore, as in lean conditions the TWCs cannot be employed, other technologies, such as EGR or lean NO_x traps, might be needed to meet NO_x limit legislation.

4 Fuels for Transportation

4.1 Fuel Properties

Transport and mobility demands and the needs of our society are mainly fulfilled with internal combustion engine vehicles powered by fossil fuels. As in the case of emission standards, the quality and methods for measuring fuel properties are strictly regulated in the majority of countries, and the limiting values are dependent on the fuel and the region. For example, in Europe, the EN228 and EN590 standards specify the fuel properties for gasoline and diesel fuel, respectively. Similarly, the ASTM D4814 (gasoline) and ASTM D975 (diesel) are the equivalent standards for fuels in the USA. In this section, the main fuel properties that are regulated in the current legislation will be discussed.

Conventionally, the fuel properties that determine fuel-powertrain suitability are the octane and cetane rating. Fuels with high octane ratings are desirable for SI engines in order to avoid abnormal fuel combustion such as pre-ignition and detonation (knock), which deteriorates combustion efficiency and could cause severe damage to the engine components. High-octane number fuels also enable the use of higher compression ratios, resulting in better thermal efficiency. On the other hand, fuels with good auto-ignition properties (high cetane rating) are more suitable for conventional CI engines, ensuring the ignition of the heterogeneous air–fuel mixture. With the development of advanced combustion technologies that hybridise compression and SI characteristics, fuels and/or fuel blends with intermediate cetane and/or octane numbers could be desirable. Fuel volatility, which is the fuel's capability to be vaporised, is also regulated as it is related to the engine's cold start performance. Low T10 (the temperature at which 10% of the fuel is vaporised) improves cold start, while high T90 (heavy HCs evaporating at high temperatures) will increase the level of PM and deposit formation.[32] Fuel lubricity, oxidation stability and cold flow properties are also regulated, as even if a fuel provides excellent performance and emissions behaviour, if the fuel lubricity, oxidation stability and cold filter plugging point are not acceptable, the usage of the fuel is not recommended unless some appropriate additives are incorporated. As the fuel injection systems are based on volumetric flow rates, fuel density is also considered as it influences the volumetric energy content of the fuel. Fuel viscosity is also regulated as fuels with high viscosity will offer a high resistance to flow, resulting in a high demand of energy to transport the fuel from the tank to the injector. Depending on the origin of the crude oil, the sulphur content can vary. Sulphur is linked with acid rain and catalyst poisoning, and therefore its content is strictly limited in the countries following the European or American standards. For instance, fuel standards in Europe impose a limit of 10 mg kg^{-1} of fuel. There are fuels that cannot be directly used in the engine because they do not fulfil some of the properties previously mentioned (*e.g.* high viscosity of vegetable oils), simply because of the regulations. In these cases, some modifications to the engine and/or the fuels have to be made. A simple approach is to directly blend the alternative fuel with the fuel that is commonly used with this specific powertrain technology. If this approach is adopted, it is recommended to test fuel miscibility and blend stability in order to avoid the risk of blend separation.

As a result of current targets for CO_2 reductions, the European Directive 2009/28/EC and the American Renewable Fuels Standard (RFS) have promoted the use of biofuels in transportation, and the use of renewable fuels has been extended. Currently, 7% of renewable oil must be blended in diesel and gasoline fuels. In Europe, this percentage must be increased to 10% by 2020.[33] According to the RFS, renewable fuel production must be 36 billion gallons by 2022, a 22.9 billion gallon increase compared to 2009.[34] The following sections present a selection of alternative fuels.

4.2 Alternative Fuels

4.2.1 Alcohols. Alcohols can be obtained from fossil fuels including natural gas, crude oil and coal, as well as from renewable feedstock. Renewable alcohols are usually classified as first generation when the feedstocks are edible materials and as second generation when non-edible feedstocks are used. Taking into account the alcohol characteristics such as their high octane rating, low cetane number, poor lubricity, high flame speed, wide flammability limits and high volatility, they are more suitable for SI engines than for CI engines. When alcohols are used as fuels in SI engines, extensive vehicle modifications are not necessary. However, issues with material compatibility in the fuel system due to the corrosive characteristics of alcohols and at cold start, part load and transient operation due to their low vapour pressure need to be addressed. Also, the lower energy content of alcohols than gasoline is a concern.[35] They are also hygroscopic (tendency to absorb water), leading to mixture separation, so special care in handling and storage is required. To take advantage of the higher octane rating compared to petrol, higher compression ratios can be employed.[36] The use of alcohols in CI engines is attractive for reducing CO_2 and PM emissions, but such use requires changes in the fuel (fuel additives to improve the cetane rating or emulsification of the alcohol in diesel),[37,38] in the powertrain to adapt the CI engine (alcohol fumigation, duplication of the injection system or the use of spark or glow plugs) and/or in the nature of the combustion process (advanced combustion operation).

Conventional studies are focused on the use of blends in diesel fuel using relatively low alcohol percentages because no major modifications in the engine are required.

Methanol is the simplest alcohol not containing carbon-to-carbon bonds. Methanol has a lower carbon/hydrogen ratio than gasoline and diesel and provides better energy efficiency, resulting in lower CO_2 emissions. Bioethanol presents some challenges relative to the high cost of production feedstock and the production process. First-generation bioethanol can be obtained from sugar cane, sugar beet, corn and other grains, but due to the issues relative to first-generation biofuels, great efforts are being made to use non-edible materials such as woody and herbaceous crops (lignocellulosic biomass) to address those issues and to develop new production processes to reduce the cost of bioethanol production.[39] The energy density of ethanol is lower than gasoline and diesel but higher than methanol, so the reduction in the vehicle's range is lower than in the case of methanol. Butanol is another primary alcohol that is also used in internal combustion engines. Until recently, not much attention was paid to butanol, possibly due to its higher production costs compared to other primary alcohols, but currently there is an increased interest in the use of butanol (particularly *n*-butanol) as a new, alternative fuel due to the possibility of using renewable feedstocks (biobutanol). In the case of butanol, one of its traditional disadvantages compared to bioethanol is its higher production costs, but new production processes utilising fermentation of agricultural feedstocks by cellulosic enzymes are being developed in order to reduce and optimise the production costs. Comparing butanol and ethanol properties, the former provides some general advantages; for example, butanol is less corrosive than ethanol, has a higher energy density, is less prone to water contamination and has a higher flame speed.

4.2.2 Biodiesel. Biodiesel is the name given to fatty acid methyl or ethyl esters produced from virgin or used vegetable oils and animal fat *via* a transesterification process.[40,41] Edible crops with high oil content were first used to produce biodiesel, but there were some issues associated with the use of arable land to grow energy crops. Thus, the use of residual feedstocks such as waste cooking oil and grease tallow has also been considered. New feedstock and production technologies have been developed based on the transformation of lignocellulosic material to liquid fuel by means of thermochemical or biological processes, as well as the use of aquatic species such as algae. For given vehicle operating conditions, the use of biodiesel increases the volumetric fuel consumption when compared to diesel due to the lower heating value of the biodiesel.[42–45] In agreement with that, most of the published studies have reported equal thermal efficiency compared to diesel.[42,46,47] PM,[40,42,48] total HC[42,45,49] and CO[42,45,50] emissions with biodiesel are usually lower. The oxygen content[51–54] and the absence of aromatic compounds[53,55] in biodiesel are the most reported factors to justify the decrease in PM, THC and CO emissions. On the other hand, the majority of the studies have reported a slight increase in NO_x with the use of biodiesel,[56–58] even though some discrepancies can be found depending on the engine technology, engine operating conditions, injection system, timing and engine maintenance and biodiesel composition, such as chain length and unsaturation level.

4.2.3 Synthetic Fuels. The scarcity of fossil fuels, the economic, technical and social issues associated with vegetable oils and the need to find cleaner and efficient liquid fuels has motivated intensive research to develop processes that are able to synthesise liquid fuels from different carbon sources. The production of synthetic liquid fuels generally consists of four steps starting from: (i) the identification of the source(s) of carbon; (ii) the production of the synthetic gas (which is a mixture of carbon monoxide, hydrogen and HC components); (iii) the synthesis process from the synthetic gas to liquid fuel; and (iv) the purification process. Synthetic fuels are categorised depending on the state of the final product as power to liquid or power to gas; depending on the source of carbon as coal to liquid, gas to liquid or biomass to liquid; and depending on the synthesis process as Fischer–Tropsch or biological power to liquid. Fischer–Tropsch is the most common process of synthesising fuels catalytically, producing a range of saturated liquid HCs from synthetic gas. The resultant liquid product is compatible for use in CI engines, being able to simultaneously reduce NO_x and carbonaceous emissions with respect to the combustion of conventional diesel fuel. Furthermore, the non-aromatic content leads to a reduction in PM.[59,60]

4.2.4 Hydrotreated Vegetable Oil. Apart from transesterification, an alternative process for converting biomass to liquid biofuels is through hydrotreating. In the hydrotreated vegetable oil (HVO) process, the hydrogen removes the oxygen from the triglycerides (vegetable oils), and as a result a mixture of paraffinic alkanes free of impurities (sulphur, metal and aromatic HCs) is produced. HVO is known as 'renewable diesel' in order to differentiate it from the biodiesel obtained by transesterification.[61] The by-product is LPG, water and CO_2, but no glycerol, as in the case of the esterification process.[61] Different feedstocks such as food vegetable oils (rapeseed oil, sunflower, soybean and palm oil), non-food vegetable oils (jatropha and algae oils) and waste animal fats can be used in the process without affecting the quality of the final fuel.[61] HVO meets diesel standards (EN590) and has similar properties to commercial diesel, although it has a lower density than pump diesel and lubricity must be improved with additives.[61,62] HVO's cetane number is between 84 and 99, compared to 53 for diesel.[62] Furthermore, HVO has higher resistance to oxidation than biodiesels.[62] HVO can be used in current diesel vehicles without engine modification. Engine tests have shown reductions of 6% and 35% in NO_x and PM, respectively, using 100% HVO in a heavy-duty diesel engine.[61] From 2007 to 2010 in Helsinki, HVO was tested in urban buses, and a 30% reduction in PM and a 10% reduction in NO_x were achieved.[63] Also, in passenger cars, considerable reductions in PM of 39% on average have been reported.[64]

4.2.5 Hydrogen. Hydrogen has been seen as a promising energy carrier for both CI and SI internal combustion engines due to its high energy density by weight (143 MJ kg^{-1}), wide flammability limits, low ignition energy and high-speed flames.[65,66] However, in terms of volume, its energy density is 3000-times lower than gasoline.[65] Hydrogen can be produced using a wide variety of methods such as methane steam reforming and coal gasification (from fossil sources or nuclear-assisted), as well as electrolysis of water from solar or wind energy.[67,68] The low energy density together with the high risk of explosion makes hydrogen storage for road transport a challenge. Several alternatives to hydrogen storage such as mechanical techniques (compressed and liquefied), chemical hydrides and adsorption materials have been investigated, but these methods are still under research as they do not yet meet governmental targets.[65] An alternative for solving the hydrogen storage challenge is its on-board production by the catalytic conversion of hydrogen carriers such as HCs[69] or ammonia.[70]

Hydrogen shows benefits in both CI and SI engines. As hydrogen is a non-carbon fuel, its addition results in lower CO, CO_2, HC and PM emissions.[69] The smaller quenching distance of hydrogen allows the flame to reach the cylinder crevices, resulting in a more complete combustion and a lower level of unburnt HCs.[71] However, the higher in-cylinder flame temperature of hydrogen combustion during normal diesel operation leads to a NO_x penalty.[69] This can be palliated with the use of EGR, as hydrogen combustion is more stable on account of the lower minimum ignition energy, which can also ease engine cold start, allowing higher EGR percentages.[71,72]

4.2.6 Natural Gas. Natural gas is an abundant resource that can be directly extracted or can be produced from coal and from biomass (biogas).[73] Methane is the main component of natural gas, with its use in the transportation sector being limited by its low energy density. In Germany, billions of euros were invested to promote the utilisation of natural gas in automotive applications. However, despite this, the initiative was not well received in the markets. The lack of infrastructure is thought to be the reason for this.[74] Similarly to the case of the German market, CNG utilisation in the American and Japanese markets was not well adopted.[74] Natural gas can be stored as compressed gas (CNG) or cryogenically liquefied (LNG) at temperatures below −161.5 °C. Natural gas is most commonly used in SI engines due to its high octane rating. It can be used in bi-fuel systems, which combine the use of petrol and natural gas. CNG and LNG readily mix with the air when they are injected, creating a complete and uniform mixing of fuel and air, which facilitates the combustion process, particularly engine warm-up. On the other hand, there is a loss of volumetric efficiency because of the air being displaced in the cylinder, resulting in a 10–20% power loss, unless DI of CNG is applied. It can also be used in dedicated natural gas engines, which can be optimised using a high compression ratio thanks to the high octane rating of natural gas and lean in-fuel operation (lambda in the region of 1.3–1.5) due to the wide flammability limits of natural gas. These factors, together with the low C/H ratio of methane and the absence of aromatics, will result in improvements in fuel economy, CO_2 emissions and PM, CO and non-methane HC species with respect to conventional SI engines operated with gasoline. However, NO_x and methane emissions are much higher than those with conventional liquid fuels in dedicated natural gas engines. Due to the low cetane rating of natural gas, its use in CI engines is less common. A pilot diesel injection (dual-fuel engine) or the addition of an ignition system and spark plugs to initiate the injection of natural gas are required.[75]

4.2.7 Liquefied Petroleum Gas. LPG is composed of a limited number of short-chain HC species such as propane and butane, with some traces of propylene, butylene, ethane and pentane, whose final composition depends on the country. In some countries, LPG has received government tax incentives, making it a relatively cheap, and it is also incentivised by encouraging the recovery of LPG from oil wells. However, governments have started to reduce the tax differential between LPG and conventional fuels, and further reductions in these tax incentives are planned over the coming years. As in the case of natural gas, a large pressurised fuel tank (around 14 bar) is required due to its reduced energy density with respect to conventional liquid fuels. LPG is instantly vaporised, facilitating the air–fuel mixing, and its consistent/simple fuel composition increases combustion efficiency, but it also displaces part of the intake air, decreasing volumetric efficiency and then power output unless forced induction (*e.g.* supercharging and turbocharging) and/or direct LPG injection are used. Due to the characteristics of LPG, including its high octane rating, it is mostly used in SI engines. LPG can be used in dual-fuel gasoline–LPG engines with the added complication of two injection systems, or in SI engines converted to work exclusively with LPG, but they cannot be fully optimised. Ideally, the engine should be designed for LPG usage using a higher compression ratio than conventional SI engines, adequate forced induction and ignition systems and optimal injection strategy. In optimised engines, and taking into account the low C/H ratio of LPG, due to the absence of aromatic compounds and the possibility of operating the engine in overall lean conditions (wide flammability limits), LPG will produce higher thermal efficiencies and lower CO_2, CO, unburnt THC and particle emissions. However, the propane and butane emissions will be higher, and there is not a clear trend in NO_x emissions, which could be equal, higher or lower depending on the operation. In the case of CI engines, only the alternative of dual-fuel technologies is feasible. The drawbacks are similar with this type of technology, such as the difficulty in optimisation and the need to maintain two fuel and injection systems.

5 Market Share

The automotive industry is a major economic and industrial force[76] and vehicle sales is a synonym of economic growth.[77] Since the economic crisis in 2009, vehicle sales have again increased 35% in the last 5 years, 46% of which are concentrated in China and the USA. By 2030, in Europe, it is expected that 297 million vehicles, including passenger cars, light commercial vehicles and heavy-duty vehicles, will be on the road, producing a total of 1022 million tons year^{-1} of CO_2 emissions. The implementation of strategies resulting in improvements in fuel economy (*e.g.* light weighting and drag reduction) and the progressive adoption of low-carbon vehicle systems (*e.g.* electric and fuel cell vehicles), being partially motivated by greenhouse emissions policies, are reflected in the CO_2 emissions downward trend,[77] as well as in the market share of road vehicles. In 2013, for the first time, the average CO_2 vehicle emissions fell below 130 g km^{-1}, and in 2014, they reached 123.3 g km^{-1}.[76] The reduction of CO_2 emissions is more noticeable in SI vehicles since 2005 due to the introduction of the GDI technology, as well as the smaller gap between the SI and CI engines' efficiencies (126 g km^{-1} and 123 g km^{-1}, respectively). In the case of passenger cars, it seems to be challenging to reach the target of 95 g km^{-1} by 2020,[76] while light commercial vehicles have already accomplished the 2017 target in 2013 of 175 g km^{-1}; the future target for 2020 will be 147 g km^{-1}.[76] The European Union is the foremost research and development investor, with 41.5 billion euros spent in 2013, followed by Japan and the USA, which invested 24 and 12.5 billion euros, respectively.[77]

In 2014, CI propulsion systems were the preferred propulsion systems in Europe, accounting for 53% of the sales in passenger vehicles and reaching 97% for light commercial vehicles.[76] In India, an emerging market, 50% of the passenger vehicles were also CI.[76] The trend was different in the USA, China and Japan, with petrol-powered vehicles dominating the markets. Gasoline dominates the US market, with a 94.6% share in 2015,[15] although the number of passenger vehicles decreased by approximately 12% from 2010 to 2014. On the other hand, the E85 (85% ethanol in gasoline by volume)-fuelled vehicle market share increased substantially in those years, and the presence of such vehicles on American roads is greater than diesel passenger cars. The E85 fleet in 2014 was around 200 000 vehicles.[20] Due to the lower CO_2 emissions of GDI engines, this technology has been widely accepted worldwide. The overall market share in 2014 in Europe was 35%.[76] GDI was first introduced in 2007 and, by 2015, 46% of vehicles had incorporated this technology in the US market,[15,20] with it being thought that this technology has not reached its maximum penetration rate yet. It has also to be noted that, in 2015, 85% of GDI cars were also turbocharged.[15]

The number of the new registrations of passenger electric vehicles, including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), increased by 70% between 2014 and 2015, with over 550 000 sales worldwide.[78] Hybrids were first introduced in 2000 in the USA.[15] In 2015, the market share of gasoline hybrid vehicles was 3% of all new vehicles,[15,76] although sales have dropped since 2013.[20] In Japan, 20% of all new sales are hybrid.[76] China overtook the USA in hybrid vehicle registrations in 2015.[78] In Europe, 1.4% of total vehicle sales were hybrid-electric, although there are substantial differences between Member States, as sales are dependent on government incentives.[76] In Norway, the electric vehicle market, including PHEVs and BEVs, accounted for 13.8% of sales in 2014, and in the first quarter of 2015, sales rose to 22.9%, making Norway the world's leading market in terms of market share. In The Netherlands, the taxation scheme based on high reductions for vehicles emitting less than 50 g km^{-1} of CO_2 has made the electric market grow significantly; 3.1% of new vehicles were PHEVs and 0.9% were BEVs in 2013. However, in 2014, electric vehicle sales decreased due to a change in the rebate scheme. Despite BEVs and PHEVs being commercially available, there are still issues regarding the battery technology, and it is thought that a 'battery breakthrough' will be needed to achieve practicality.[79] A summary of the market share by fuel is reported in Figure 2.[76]

Registrations of heavy-duty vehicles, including trucks, vans and buses, were recorded at 18.4 million in 2014: 26.9% in America, 13.3% in Europe, 54.2% in Asia and 5.6% in the Middle East.[77] Truck and bus sales in the EU in 2014 were 0.3 million, which was 30% lower than sales before the economic crisis, but showing an increasing trend over the preceding 5 years. In USA, sales of trucks also increased notably from 2011 to 2015.[20] Class 3 (light-duty trucks weighing between 4536 and 6350 kg) and Class 8 (heavy-duty trucks whose weight exceeds 14 969 kg) sales increased by 45%, as well as sales of Class 4–7 trucks increasing by 47%. Most of the vehicles corresponding to Classes 3–8 were powered by CI engines (74% in 2014).[20] Almost 100% of Class 8 trucks were diesel, while the use of diesel for Class 4 trucks has fallen to 66%. Significant efforts are being made to reduce fuel consumption in heavy-duty vehicles in the USA. Electrification during truck idle stops can reduce fuel consumption significantly.[20] For Class 8 trucks, aerodynamic drag is a large source of energy loss. Thus, devices such day cab roof deflectors, sleeper roof fairing, chassis skirts or cab extenders have been adopted. Fuel consumption improvements of between 2% and 10% have been achieved.[20]

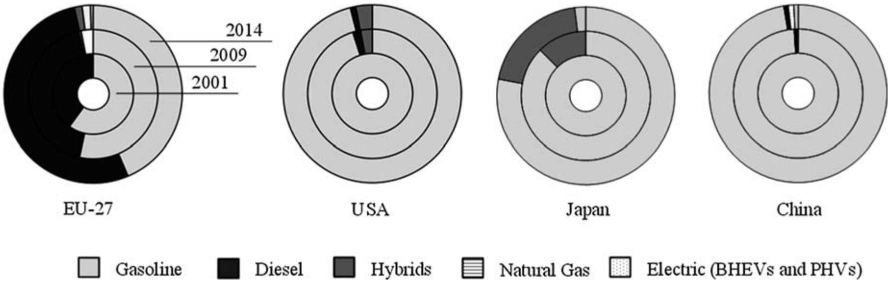

Figure 2 Market share by fuel in passenger cars.
Reproduced with permission from ref. 76.

Amongst the technologies used to achieve better fuel economy, cylinder deactivation[15,20] accounted for 13% of production, while stop–start was 7% for non-hybrid vehicles and 9% when hybrids are considered.[15] Turbocharged engines achieved 18% of the market share in 2015.[15] Cooled exhaust-gas recirculation accounted for 5% and turbocharging and downsizing for between 12.1% and 24.7%, depending on the vehicle attributes.[20] In 2015, almost 20% and 12% of cars and trucks, respectively, were turbocharged.[15] For the near future, two models of fuel cells are expected for 2016–2018 with similar ranges to conventional vehicles.[20]

6 Future Trends

6.1 Advanced Combustion Strategies

The classical concept of combustion is currently changing and moving towards hybrid combustion between conventional CI (diesel) and SI (gasoline) engines. Maintaining the high efficiency and high compression ratio of the CI engine combined with the premixed/ideally homogeneous charge of the SI engine to avoid soot formation without the need for spark and throttle is the aim of the new, advanced combustion strategies. In order to achieve this aim, the combustion must occur in low-temperature combustion regions where the formation of soot and NO_x is limited.

The first attempt to apply this combustion concept to four stroke engines is known as homogeneous charge CI (HCCI) or controlled auto-ignition, which began in 1970,[80,81] although it was not until the 1980s that this strategy became popular.[82,83] In HCCI, the air and fuel are premixed to form a homogeneous mixture, as in SI engines, with overall lean local equivalence ratios, as in CI engines, typically lower than 0.5, which is auto-ignited during the compression stroke. To produce lean charge, high percentages of EGR are used. The combustion temperature must be maintained at between 1500 and 1800 K; temperatures higher than 1500 K ensure the full conversion of CO to CO_2, while temperatures lower than 1800 K limit NO_x formation.[84,85] The efficiency of HCCI is similar to that of CI engines, and while NO_x and PM are drastically reduced, HC and CO emissions are increased equivalently due to the low in-cylinder temperatures.[86] Moreover, as the combustion is dominated by chemical kinetics, controlling the start of combustion and the rate of heat release is a major challenge, resulting in a narrow operation range. At low loads, the engine suffers from ignition difficulties and low combustion efficiency due to the high-dilution and low-temperature conditions. On the other hand, at high load, the fast heat release leads to intense cylinder pressure rates, which could produce ringing and engine damage.[19,80,84–86] HCCI can be performed with both diesel and gasoline fuels.[84] Gasoline is more volatile, promoting mixture homogeneity; however, it is highly resistant to auto-ignition, in contrast to diesel.[87] Therefore, an optimal fuel that facilitates mixture formation and optimal auto-ignition properties is needed for successful HCCI operation.

To overcome HCCI obstacles while maintaining the high thermal efficiency and reduced NO_x and PM, several approaches have been initiated. Partially premixed combustion or premixed charge CI (PCCI) assists in the control of the combustion event. Multiple injection events could be also applied, in which part of the fuel is injected early during the compression stroke to precondition the combustion chamber with a homogeneous fuel–air mixture, and a late second injection creates a stratified region in order to start the ignition. This heterogeneity is needed to ensure combustion.[88] However, the high reactivity (high auto-ignition tendency quantified by cetane number) of diesel obstructs the homogeneous premixing of the charge, and high rates of EGR—more than 70%—are required.[80] Fuels with high octane numbers, or gasoline-like fuels, have been found to be more suitable for PCCI.[87,88] The performance of gasoline and ethanol in PCCI combustion mode has been investigated,[89] with 3.3% and 10.3% reductions in fuel consumption achieved with gasoline and ethanol fuelling, respectively, as well as significant reductions in NO_x and soot. Also, moderate blends of butanol (50–70% butanol in diesel) show potential for PCCI.[90] The high volatility of butanol favours the premixing between the air and the fuel, considerably reducing soot emissions below Euro 6 levels; however, NO_x emissions are increased above the standards. CO and HC levels were similar to diesel over the whole operation range and indicated that efficiency up to 50% can be achieved with butanol–diesel blends.[90] PCCI can improve the engine's efficiency; nevertheless, it is not exempt from challenges, and research is ongoing.

A different combustion strategy is the so-called reactivity-controlled CI. This combines the separate injection of two fuels with different reactivity levels (*i.e.* diesel-like fuels with high auto-ignition propensity and gasoline-like fuels with high volatility for good mixture formation but low auto-ignition propensity). First, the low-reactivity fuel is port injected to create a homogeneous mixture between fuel, air and the recirculated exhaust. Then, the high-reactivity fuel is directly injected in the combustion chamber in one or more injection events to control the start of the ignition.[91] This strategy provides better combustion control than HCCI or PCCI and the engine can achieve a thermal efficiency of up to 60%.[91] Current research is focused on the optimisation of the fuels used to achieve fuel stratification for controlled combustion and low emissions in light- and heavy-duty vehicles.[92,93]

If available commercial gasoline is used in CI engines, the combustion strategy is known as gasoline CI (GCI).[94,95] GCI faces the same load limitation as HCCI: at low loads it suffers from misfiring, while at high loads knocking is produced.[95] The fuel injection strategy varies between studies, ranging from multiple injections[96] to single injection.[94] Also, different injectors have been used: high-pressure injectors (typically from CI engines)[94] and GDI injectors.[96] At low injection pressures, less wall wetting is produced, which is an important source of soot formation. Furthermore, lower injection pressures reduce parasitic losses and fuel injection system costs.[96]

6.2 Cylinder Deactivation

Deactivation of one or more cylinders at low engine load conditions has also been researched in order to increase the load in the 'active/running' cylinders and shift the overall operation towards minimal fuel consumption areas,[97–99] as shown in Figure 3.[97] Deactivating some of the cylinders, usually half,[98] forces the active cylinders to operate at higher mean effective pressures in order to reach the torque demand, thus leading to reduced pumping losses.[98,100] The fuel injection and ignition systems are cut off in the deactivated cylinders, which only compress and expand the intake air, reducing friction and heat losses.[98] The most effective cylinder deactivation strategy is to also disable moving parts such as valves and pistons in order to further reduce friction losses.[97,101] This is normally applied to engines with more than four cylinders, as noise vibration and harshness (NVH) remains an issue for these engines, according to vehicle manufacturers.[98] Cylinder deactivation is a technology that is currently used by several vehicle manufacturers. Cylinder deactivation is reported to reduce fuel consumption by between 4.7% and 6.5%.[20] It is normally combined with valve phasing technologies such as single overhead camshafts, dual overhead camshafts or overhead valves to achieve further fuel consumption reductions.[98]

Cylinder deactivation can be used in both gasoline and CI engines, although the benefits for each engine type are different. For SI engines, cylinder deactivation reduces pumping losses at low loads, improving the brake-specific fuel consumption. On the other hand, in CI engines, apart from the benefits in fuel consumption, the exhaust temperature increases when only some of the cylinders are fired, improving the after-treatment performance.[100] Cylinder deactivation technology will be improved in terms of the dynamic deactivation of individual cylinders.[99] Instead of deactivating the cylinders symmetrically in order to avoid NVH and torque fluctuations, new systems currently under development change the active

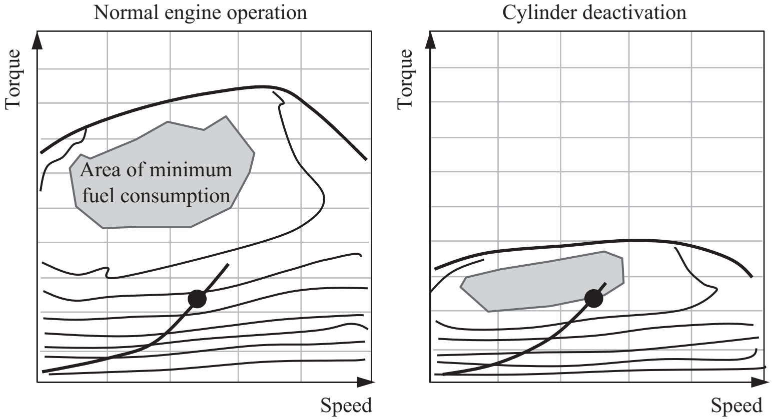

Figure 3 Effect of cylinder deactivation on engine map and fuel consumption. Adapted with permission from ref. 97.

cylinders continuously. The advantages of these systems over conventional cylinder deactivation are the uniformity of engine operation temperatures, operation with a fully open throttle, reduced NHV and extended use of cylinder deactivation to small engines with an odd number of cylinders.[99]

6.3 Variable Compression Ratio

The compression ratio is defined as the ratio of maximum volume to minimum volume (volume of the combustion chamber).[6] Typical compression ratio values are between 8 to 12 in SI engines and between 12 and 24 in CI engines.[6] Higher compression ratios are desirable as more power for the same air–fuel mixture can be extracted due to the higher thermal efficiency.[6] However, there is a maximum compression ratio achievable for both gasoline and CI engines. For SI engines, knock limits the compression ratio. In diesel engines, the constraints come from the material resistance to harsher temperature and pressure conditions. Today, the compression ratio is fixed depending on the cylinder geometry.[20] However, new developments have been able to alter the engine geometry, increasing the compression ratio under partial and light-load conditions or reducing it under heavy-load conditions, thus increasing efficiency.[20]

6.4 Variable Valve Actuation and Atkinson–Miller Cycles

Variable valve actuation is designed to control the lift, duration and timing of the intake and exhaust valves. There are two approaches: VVT and variable valve lift (VVL). These technologies can allow the unthrottled operation of SI engines and can aid in depleting pollutants coupled with other technologies, such as Atkinson cycles.[99,102]

VVT alters the timing or phase of the intake and/or exhaust valves.[81,103] The advantage of this is the reduction in pumping losses, which leads to higher volumetric efficiency, increasing the torque output while reducing fuel consumption.[103] Control of the internal residual exhaust gases is also achieved.[81] According to the US Department of Transportation, in 2010, 86% of passenger vehicles and light trucks had VVT.[81] Currently, almost all vehicle manufacturers have adopted this technology.[15] VVL regulates the height lift of the valves. Further advantages in reduced pumping losses at low loads can be achieved with VVL when compared to VVT.[103]

With the development of VVT and VVL, it has been possible to recover 'old ideas' that seemed inefficient years ago. James Atkinson (1846–1914) developed a long expansion engine that could provide high efficiency, but also suffered from several mechanical issues.[6] The Atkinson or over-expanded cycle attempts to recover the energy contained in the exhaust gas at the time of exhaust valve opening, thus increasing the indicated work per cycle.[6] Currently, the over-expansion is obtained through the use of VVT or VVL. The intake valve remains opened longer during the intake stroke and is closed during the compression, increasing the work extracted per cycle. However, the piston pushes part of the charge back to the intake manifold, increasing the geometric compression ratio as the trapped mass of charge is reduced, lowering torque and power output.[6,99,104] To maintain vehicle performance, it is necessary to increase the engine displacement or to use full-hybrid systems in which the electric propulsion motor re-establishes the torque.[99] Miller cycles, developed in 1957 by Ralph Miller, use the concept of the Atkinson cycle in supercharged engines.[105]

6.5 Stop–Start

In real driving conditions, idling contributes to up to 25% of the total emissions. Vehicle idling is associated with populated places such as roadways, traffic lights, bus stops, rest areas, drive-through restaurants and schools.[106] Vehicles during idle operation emit CO, HC, PM and NO_x to the atmosphere, as well as consuming a significant quantity of fuel.[106] Stop–starts reduce the idling time by shutting the engine down when the vehicle is stopped in traffic, reducing fuel consumption and emissions. The engine automatically restarts when the driver releases the brake pedal or presses the clutch.[99,107] The system is inherent in hybrid vehicles, but it is also used in internal combustion engine-powered vehicles.[15,108] The objectives of the stop–start system are to reduce fuel consumption and pollutant emissions, to achieve fast and smooth engine restart, to minimise the impact on driver's experience and to ensure the functionality of auxiliary systems.[108] Fuel economy can be improved by 3.5%.[108] The main challenges that stop–start systems face are the need for a starter motor and battery that are suitable for higher-duty cycles, safety issues relating to unwanted engine restarting, guaranteeing engine restart when required (driver's change of mind) and low NVH.[107,108] A 12 V electrical system is required for auxiliary systems, such as A/C systems, while the engine is stopped.[107] Furthermore, the cost associated with stop–start must be justified by the CO_2 reductions.[108] In 2015, the stop–start technology achieved a market share of 7.4% for passenger cars and 5.5% for light trucks in the USA.[20]

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