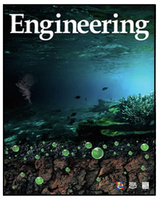
Engineering 5 (2019) 510–518

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng



Research
Engines and Fuels—Review

Development of Fuel/Engine Systems—The Way Forward to Sustainable Transport

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ARTICLE INFO

Article history:
Received 20 June 2018
Revised 24 January 2019
Accepted 25 January 2019
Available online 28 March 2019

Keywords:
Transport energy
Internal combustion engines
Gasoline
Diesel

ABSTRACT

The global demand for transport energy is large, growing, and primarily met by petroleum-derived liquid fuels powering internal combustion engines (ICEs). Moreover, the demand for jet fuel and diesel is projected to grow faster than the demand for gasoline in the future, and is likely to result in low-octane gasoline components becoming more readily available. Significant initiatives with varying motivations are taking place to develop the battery electric vehicle (BEV) and the fuel cell as alternatives to ICE vehicles, and to establish fuels such as biofuels and natural gas as alternatives to conventional liquid fuels. However, each of these alternatives starts from a very low base and faces significant barriers to fast and unrestrained growth; thus, transport—and particularly commercial transport—will continue to be largely powered by ICEs running on petroleum-based liquid fuels for decades to come. Hence, the sustainability of transport in terms of affordability, energy security, and impact on greenhouse gas (GHG) emissions and air quality can only be ensured by improving ICEs. Indeed, ICEs will continue to improve while using current market fuels, through improvements in combustion, control, and after-treatment systems, assisted by partial electrification in the form of hybridization. However, there is even more scope for improvement through the development of fuel/engine systems that can additionally leverage benefits in fuels manufacture and use components that may be readily available. Gasoline compression ignition (GCI), which uses low-octane gasoline in a compression ignition engine, is one such example. GCI would enable diesel-like efficiencies while making it easier to control nitrogen oxides (NO_x) and particulates at a lower cost compared with modern diesel engines. Octane on demand (OOD) also helps to ensure optimum use of available fuel anti-knock quality, and thus improves the overall efficiency of the system.

1. Introduction

Modern society is critically dependent on the transport of goods and people. In 2015, the world had around 1.1 billion light-duty vehicles (LDVs) and 380 million trucks [1], and these numbers are expected to grow, mostly in non-OECD (short for Organization for Economic Co-operation and Development) countries such as India and China, to 1.7–1.9 billion by 2040 [1–4]. Transport accounts for about 20% of all energy used and around 23% of global carbon dioxide (CO_2) emissions [5]. However, transport contributes only around 14% of global greenhouse gas (GHG) emissions—an amount that is comparable to the share of livestock farming for meat and dairy products [6]—if gases such as methane are included. At present, internal combustion engines (ICEs) power transport almost entirely (> 99.9%), with reciprocating engines powering land and marine transport, and jet engines powering air transport. Spark ignition (SI) engines power around 80% of all passenger cars across the world [4], while diesel engines dominate the commercial sector (road and marine use). LDVs use around 44% of the global transport energy [7] although they are much greater in number compared to commercial vehicles.

Petroleum-derived liquid fuels currently provide around 95% of transport energy, and roughly 60% of crude oil produced is used to make transport fuels [2–4,7]. The demand for transport fuels across the world is very large, at around 4.9 billion liters each of gasoline and diesel and 1.3 billion liters of jet fuel *each day* [8], with an

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https://doi.org/10.1016/j.eng.2019.01.009

expected yearly growth of around 1% [2,7]. Changes in the transport sector are occurring because of increasing demand driven by increasing population and prosperity; the need to ensure energy security, control GHG emissions, and improve local air quality; and in response to consumer preferences and demands. The importance of each of these drivers for change will differ in different countries and at different times. The battery electric vehicle (BEV) and the fuel cell could replace ICEs, and fuels such as natural gas and biofuels are possible alternatives to conventional liquid fuels made from crude oil. However, these alternatives to the existing system all start from a very small base, face critical barriers to unrestrained and quick growth [8], and—even by 2040—are not projected to account for more than around 10% of global transport energy [2,3,7]. It is important that these alternatives be assessed on a life-cycle basis to ensure that the environmental and other benefits are real, and that the burdens are not simply shifted from the engine tailpipe to somewhere else.

Thus, transport will be powered largely by ICEs using mostly petroleum-based fuels for decades to come [2,3,7,8]. Furthermore, over this time scale, the shortage of oil will not constrain growth in transport; known reserves of oil have been increasing faster than consumption over the last several decades, and the current reserves should last for at least the next 50 years at current consumption rates [8,9]. Therefore, it is imperative to improve the efficiency, environmental impact, and affordability of ICEs, which will mostly continue to power transport in the foreseeable future.

In general, there is much more scope for reducing the fuel consumption of LDVs than of commercial vehicles, with the result that the demand for transport energy in the commercial sector is expected to rise much faster than demand in the passenger car sector in future [2,3]. More oil will have to be processed to produce the increasing amounts of diesel and jet fuel needed for the commercial sector, and the production of low-octane gasoline components, which are collectively known as naphtha, will increase proportionately. Naphtha is usually processed further to make gasoline, although it is also used to make petrochemicals. Since gasoline demand is not expected to increase at the same rate as the demand for diesel and jet fuel, it is highly likely that the availability of naphtha will increase in future. Refineries will be required to make very large investments to meet this changing fuel-demand structure, and will also need to find an economic use for naphtha in transport fuels in order to maintain their commercial viability [10,11].

A great deal of potential exists for improving the efficiency of ICEs via improvements in combustion, control, and after-treatment systems. Fuel consumption in SI engines [2] can be further reduced in future by partial electrification in the form of hybridization, which is likely to be widely deployed [2]. Hybridization allows an SI engine to run more efficiently and enables the recovery of energy lost in braking. Heavy-duty vehicles are less likely to have the driving modes with frequent starts and stops that are more common to passenger cars, and usually run on diesel engines, which are already efficient; thus, electric hybridization will be less beneficial in such vehicles. However, if future engines are not obliged to run on current market fuels, there is greater scope in developing engines and fuels together for increased benefits in efficiency and emissions at affordable cost. Such approaches could also provide a pathway to use fuel components such as low-octane gasoline components, which are likely to be in surplus and could therefore be available at a lower price to the consumer.

This paper discusses the issues described above, but draws heavily on previous reviews by this author [8,12–14]. The paper first discusses current fuels and engines and current projections on fuel supply and demand in brief. It then discusses future developments in ICEs and fuel/engine systems.

2. ICE fuels and combustion systems

Details about engine fuels and combustion processes have already been discussed in several books [15–18], so this section contains only a brief summary.

2.1. ICE fuels

Transport has evolved to be almost entirely powered by liquid fuels because of their high energy density and ease of transport and storage. For example, at normal temperature and pressure, a liter of gasoline contains over 700 times more energy than a liter of natural gas and over 3100 times more energy than a liter of hydrogen gas. In order to carry enough mass on a vehicle to get a reasonable range, a great deal of energy must be used to liquefy or compress a gaseous fuel. Over the past century, an extensive global network worth trillions of dollars, which will be difficult and expensive to replace or replicate, has developed around the use of liquid fuels for transport.

Transport fuels are mostly made by refining crude oil (petroleum). The first step is the distillation of the crude oil. When oil is heated above ambient temperature, gases dissolved in the crude oil are released; these gases make up liquid petroleum gas (LPG). LPG can be up to 2% of crude oil, and consists mostly of propane and some butane. The fraction of crude oil that lies within the gasoline boiling range, with boiling points between ~20 and ~200 °C, from the initial distillation is known as straight run gasoline (SRG). Diesel fuels are made up of heavier components with boiling points ranging from ~160 to ~380 °C. Heavy components, with boiling points higher than 380 °C, can constitute 40%–60% of the weight of crude oil, depending on the source of the oil. In the refinery, these heavy components are first "cracked" into smaller molecules, which are further processed to produce useful products, for example by reducing sulfur or changing their octane/cetane number. The products in the gasoline boiling range from different parts of the refinery are collectively known under the generic term "naphtha." Naphtha is usually processed further to increase its octane number; it is also used in the petrochemicals industry. Other non-petroleum components such as biofuels and high-octane components such as methyl tertiary butyl ether (MTBE) and ethanol are blended with refinery components, along with some fuel additives, to meet the required fuel specifications [15,16].

Knock, an abnormal combustion phenomenon, limits efficiency in SI engines. Hence, gasolines need to have high anti-knock quality, as specified by the research octane number (RON) and motor octane number (MON) [15,19,20]. Most market gasolines have RON > 90. For diesel fuels, autoignition quality is measured by the cetane number (CN). Diesel fuels generally require a high CN because they need to autoignite easily; practical diesel fuels have CN > 40. The higher the RON of a fuel, the lower is its CN, and vice versa [15,19]. The CN of jet fuel is lower than that of conventional diesel fuel, and jet fuel is blended using more volatile components in the diesel boiling range. Marine transport fuels are blended from the heaviest components in the fuel pool, and have a high sulfur content. In the future, marine engines could be forced to run on conventional diesel fuel because of current moves to reduce the sulfur content of marine fuels; such a shift would further contribute to increasing the demand for diesel fuel in the future.

Gasoline-like fuels are defined in this paper as fuels with CN < 30 or RON > 60—that is, as fuels within the gasoline autoignition range, as specified in Ref. [19].

2.2. Engine combustion systems

Two major practical ICE combustion systems are used in land and marine transport. In SI engines, an electric spark initiates flame propagation to release energy from a mixture of fuel and air that is compressed after premixing. In modern SI engines, the fuel/air ratio must be maintained at stoichiometric levels to enable the three-way catalyst to be used effectively in order to reduce carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x) in the exhaust to acceptably low levels. In terms of mass, soot emissions from SI engines are negligible; however, the number of nanoparticles (i.e., particles less than 100 nm in diameter) is of increasing concern. Gasoline particulate filters are likely to be increasingly required in future to address particulate emissions from SI engines. For any given fuel, the maximum temperature and pressure that can be reached ahead of the expanding flame front, in the "end gas," are limited by knock, which is caused by autoignition in the end gas [15,19,20]. Knock depends on the time available for autoignition and on the anti-knock quality of the fuel. Load is reduced in SI engines by the use of a throttle to reduce airflow, since the amount of fuel energy cannot be reduced independently of airflow due to the fixed air/fuel ratio. In contrast, compression ignition (CI) engines do not use a throttle because load is controlled by controlling the amount of fuel that is injected. SI engines compress a mixture of fuel and air; in contrast, CI engines compress mostly air during the compression stroke [17,18]. As a result, pumping losses are higher in SI engines than in CI engines. For all these reasons, SI engines convert only 20%–25% of the fuel energy to motive power over a typical driving cycle and are less efficient compared to CI engines. However, their impact on pollution in terms of HC, NO_x, CO, and particulate mass is low because of the use of effective after-treatment. The engines used in commercial transport are larger and heavier than those used in passenger cars, so they have to run at lower speeds. Knock is more likely to occur in larger engines at lower speeds than in smaller engines running at higher speeds because of the greater amount of time available for autoignition. Hence, SI engines are not usually used in commercial transport.

In CI engines, fuel is injected into the high-pressure and high-temperature environment near the top of the compression stroke and heat release is initiated by autoignition as the fuel mixes with oxygen. At present, all practical CI engines use diesel fuel and are diesel engines. Soot (particulates) and NO_x emissions are a significant problem for diesel engines, and technology such as complex after-treatment and a high-pressure injection system are needed to control them. Modern diesel engines are hence much more expensive than SI engines of similar size, although they are more efficient.

Recently, there has been much interest in homogeneous charge compression ignition (HCCI) combustion. In an HCCI engine, fuel and air are fully premixed, as in an SI engine, but heat release occurs by autoignition, as in knock in an SI engine. The thermal efficiency of HCCI engines is very high but they are limited to operating at low loads (i.e., lean mixture strengths) because of excessive pressure rise rates at richer equivalence ratios. Friction losses are proportionately higher at lower loads, and the brake efficiency of HCCI engines, at the loads they can operate, will be lower. Greater mixture or temperature stratification can increase the upper load limit of an HCCI engine but such engines should not be termed HCCI engines because the mixture is not homogeneous. In HCCI engines, at the low loads they are constrained to run, the soot and NO_x levels can be exceptionally low. In diesel and SI engines, in-cycle control over the phasing of heat release is provided by the timing of the final fuel injection and of the spark, respectively. Such in-cycle control is not possible in HCCI combustion, which makes its implementation difficult in practical engines. If a certain level of inhomogeneity/stratification is obtained by the late injection of the final fuel pulse, in-cycle control of combustion can be restored and HCCI-like combustion—in which fuel and air are "premixed enough" to result in low soot and NO_x—can be obtained. Gasoline compression ignition (GCI) and reactivity-controlled compression ignition (RCCI) are two such approaches, and are discussed below.

The evolution of new technology such as GCI requires collaboration among all stakeholders—including the auto and oil industries and governments—and is affected by strategic issues such as the supply and demand of transport energy.

3. Future development

Current efforts to improve ICEs are focused on using existing market fuels. This is clearly essential because it is very difficult to change both fuels and engines simultaneously in the marketplace.

Significant developments are underway to improve the efficiency of SI engines almost to the level of diesel engines [21–25]. For example, fuel consumption for the best-in-class passenger car in the US market is already around 16% lower than the US fleet average for cars of similar size and performance [21]. Approaches under development include lean burn, downsizing, and turbocharging, along with CI using market gasolines [24,25]. Many supporting technologies are also being developed [21–23] to ensure that these efficient engines meet stringent exhaust emissions requirements. The gasoline direct-injection compression ignition (GDCI) engine using partially premixed compression ignition (PCI) has demonstrated diesel-like efficiency [24] using US market gasoline. The expectation is that combustion system developments alone will reduce fuel consumption by around 30%, in LDVs in comparison with the 2015 fleet average using SI engines [21–23]. With additional technologies such as light-weighting and hybridization, this improvement could reach around 50%. As fuel consumption decreases, the GHG impact of ICEs will decrease proportionately, and will reduce any advantages BEVs running on renewable electricity might have in terms of GHG emissions.

Similarly, after-treatment systems have been and continue to be developed to reduce exhaust pollutants such as particulates, NO_x, CO, and HC [26–28]. For example, modern diesel particulate filters (DPFs) and gasoline particulate filters almost entirely eliminate particulates from ICE exhausts [27,28]. A warmed-up catalyst in a modern car can reduce HC emissions in the exhaust to almost zero—certainly well below ambient air levels in many urban areas [26]. Even NO_x levels in diesels can be reduced to levels 10 times lower than European limits set for 2020 with a modern exhaust catalyst and intelligent management of combustion temperatures and modes [28].

3.1. Fuel implications in the short term

Engine combustion system developments also have implications for fuels. For example, the design trend in SI engines has been to increase the pressure in the cylinder for a given unburned gas temperature in order to improve power density and efficiency. This makes autoignition in the end gas, leading to knock, more likely. High anti-knock fuel quality will help to avoid knock and enable higher efficiency SI engines. Pressure to increase the anti-knock quality of gasolines in order to enable high-efficiency SI engines will grow. For example, there are suggestions [29] that by 2040 all gasoline in the United States should have RON > 98, whereas currently US regular, the most commonly used gasoline in the United States, has a RON of around 92. Whether such a change will bring about benefits in terms of GHG emission reductions needs to be assessed on a life-cycle basis, and the answer may differ for different refinery configurations. Such increases in RON will require big changes and investments in refineries and will lead to a further increase in the availability of low-octane gasoline components such as naphtha [10,11] because the opportunity to blend them in gasoline will decrease. The importance of high-octane components such as ethanol, MTBE, di-isobutylene, and methanol will also increase.

The question of how fuel anti-knock quality should be defined in such modern engines is an important one [14,19,20], as this definition has major implications for fuels manufacture, which is geared toward meeting gasoline anti-knock specifications. Gasoline anti-knock quality is currently defined by RON and MON. These are measured by comparing the gasoline with blends of iso-octane and *n*-heptane, known as primary reference fuels (PRFs), in the single-cylinder Cooperative Fuels Research (CFR) engine, according to test procedures set by the American Society for Testing and Materials (ASTM). For practical fuels, RON is higher than MON; the difference between them is known as the sensitivity, *S*. The MON test is run at a higher intake temperature compared to the RON test and the pressure for a given unburned mixture temperature is lower in the MON test than in the RON test. Practical gasolines contain aromatics, olefins, and oxygenates, which respond very differently in chemical kinetic terms to increasing pressure in comparison with the PRFs that are used to define the RON and MON scales. Practical fuels are much more prone to autoignition and knock under the MON test conditions than PRFs. However, SI engines have been moving away from the MON test conditions, as designers have increased the mass of air (pressure) in the engine without increasing the unburned gas temperature too much in order to increase efficiency and power density [19,30]. In fact, a lower MON fuel, for a given RON—that is, a fuel with higher sensitivity for a fixed RON—has better anti-knock quality in modern engines [14,19,20]. However, in many areas including the United States and Europe, the MON is considered to contribute to anti-knock quality—that is, a high MON is considered desirable. As engine designers seek to further improve engine efficiency, this mismatch between specifications and engine requirements will widen and will have to be addressed. One approach might be to replace the octane scale with a different scale based on toluene/*n*-heptane mixtures (toluene reference fuels, TRFs) rather than PRFs. The fuel would be tested using the RON test and assigned a toluene number (TN), the volume percent of toluene in the TRF that matches the test fuel for knock [31]. At the very least, countries that specify gasoline anti-knock quality using RON alone, such as Japan, should not introduce a minimum MON specification.

In addition to knock, conventional fuel-related concerns such as spark ignition, flame development, deposit formation and control [12], and pollutant formation will continue to be of importance as SI engines seek ever higher efficiency. There is persistent pressure on fuel manufacturers to reduce sulfur levels in both gasoline and diesel to enable effective after-treatment systems. Fuel additives [12,32] are routinely used to control deposits in the fuel system.

There is greater scope for the development of affordable and highly efficient new fuel/engine systems to meet increasingly stringent requirements on GHG emissions and local air quality if engines are not confined to using current market fuels. Of course, such a shift will require cooperation between auto and oil industries and other stakeholders, and will probably happen in the mid to long term. Some of these possibilities are discussed below.

3.2. Gasoline compression ignition

This section borrows heavily from a recent review of GCI [33], which also carries a more comprehensive list of relevant papers.

Diesel engines have a lower GHG footprint because of their high efficiency; however, they bring increasing concerns regarding particulate and NO_x emissions. Diesel fuel ignites very quickly after injection and burns in a quasi-steady jet diffusion flame [34] before it has a chance to mix sufficiently with oxygen in the cylinder, under most operating conditions. There is a much better chance of minimizing soot formation if the equivalence ratio, φ, of the mixture packets where combustion occurs is no greater than around 2 [34]. If the combustion temperatures are kept below around 2200 K, usually by using exhaust gas recirculation (EGR) in practical engines [34,35], NO_x formation can be minimized.

Most of the soot formed is oxidized inside the diesel engine. Both the oxygen content and the temperature in the cylinder decrease if the EGR level is increased in order to control NO_x. Then soot oxidation decreases and, if any soot has been formed, the engine-out particulate matter (PM) or soot increases, leading to the well-known PM/NO_x tradeoff in diesel engines. If fuel and oxygen are mixed sufficiently well before combustion starts, soot formation can be reduced or avoided. NO_x emissions can then be controlled using EGR without increasing engine-out soot. However, such a combustion system increases the engine-out HC and CO, which must be controlled with appropriate after-treatment.

The final injection of fuel must be completed sufficiently before combustion starts in order to avoid soot formation. Partially premixed combustion (PPC) or PCI to avoid soot formation has been defined by Ref. [36] as occurring when the final fuel injection is completed sufficiently before combustion starts in order to ensure that the engine-out smoke has a filter smoke number (FSN) of below 0.05. A time constant relevant to PPC is the ignition dwell, IDW = SOC − EOI, where SOC and EOI are the crank angles at the start of combustion and the end of the final fuel injection, respectively. The IDW must be positive in PPC.

When diesel fuel is used, PPC can be promoted by reducing the injection pulse width and accelerating mixing by increasing the injection pressure at a given operating condition. Even with modern injection systems, PPC is only possible at low loads if diesel fuel is used, and NO_x and particulates must be controlled by sophisticated after-treatment systems in conventional diesel engines. The global mixture strength is lean of stoichiometric and the engine exhaust always has oxygen in diesel engines; it is particularly difficult to reduce NO_x in such an oxygen-rich environment. The difficulties presented by the use of diesel fuel can be addressed by sophisticated after-treatment technology, which makes the modern diesel engine expensive. Pollution-reduction strategies can also increase fuel consumption. For example, when the exhaust temperature is low at low loads, the DPF accumulates soot that must occasionally be burned off to regenerate the DPF using extra fuel.

In a single-cylinder heavy-duty engine, Kalghatgi et al. [37,38] have demonstrated that extremely low soot and NO_x could be obtained if gasoline-like fuels with greater resistance to autoignition were used. This is GCI, which is in fact a more practical way of achieving HCCI-like combustion. The important difference is that the fuel and air are not fully premixed in GCI, unlike in an HCCI engine. Combustion phasing can be controlled in-cycle as in a diesel engine by the timing of the last fuel injection (when multiple injections are used). This ensures that there is enough inhomogeneity within the cylinder to ensure that autoignition starts even under operating conditions when autoignition and hence HCCI combustion might not be possible at all (e.g., low load). Thus, in GCI, while fuel and air are “premixed enough” to ensure low or no soot formation, they are not fully premixed. Several other research groups have also demonstrated that if more mixing time is enabled by the use of gasoline-like fuels with greater resistance to autoignition, the control of particulates and NO_x in CI engines is much easier [24,39–56].

3.2.1. Advantages of GCI engines

The injection system in a GCI engine should be cheaper than in a modern diesel engine because GCI engines do not require high injection pressures. In fact, in such engines, lower injection pressures improve the stability of combustion at low loads, presumably by enabling increased inhomogeneity [33,48,51]. In GCI engines, the focus of after-treatment shifts from the simultaneous control of soot and NO_x to the oxidation of HC and CO. A GCI engine, like a diesel engine, will run lean overall and the exhaust will contain oxygen; thus, the oxidation of CO and HC should be easier to accomplish than the reduction of NO_x. A DPF might be needed to cope with higher soot emissions at high loads in a GCI engine. However, soot is not formed in GCI engines at low loads, and the DPF does not accumulate soot and will need to be regenerated less often, if at all. Although soot might be formed at high loads, the DPF might be mostly self-regenerating, without requiring extra fuel, as the exhaust temperature may be high enough. Hence, the after-treatment system could be simpler and cheaper in a GCI engine than in a modern diesel engine.

GCI engines have been demonstrated to have very high efficiencies. Indicated fuel efficiencies of up to 56% have been measured in a heavy-duty engine [39]. Fuel consumption could be reduced by 25% or more in light-duty engines over an operating cycle [24,45,46] compared with running the engine on gasoline in SI mode. Further efficiency improvements might be possible in light-duty engines in comparison with conventional diesel operation. For example, in light-duty diesel engines using diesel fuel, noise is a problem at low loads because combustion is initiated by autoignition in a rich mixture. This is true even if the fuel injection is completed before combustion, because of the lower ignition delay (ID, ID = SOC − SOI, where SOI is the crank angle at the start of injection) of the diesel fuel [48,51,52]. In modern diesel engines, pilot injection is employed to increase temperatures in order to promote more diffusive combustion of the main fuel injection to alleviate noise; however, doing so results in lower efficiency and a greater amount of soot, which loads up the DPF. This negative result can be avoided by using fuels with a high ID because autoignition occurs in a much leaner mixture than diesel fuel; engine noise is low because the pressure rise rate is very low at low loads [33,48,51], and a pilot injection will not be needed. For a given speed, soot and NO_x can be controlled at higher loads in GCI compared with a diesel engine, and the engine could be downsized to meet the requirements over a given operating cycle. There might be further benefits in efficiency because lower injection pressures reduce parasitic losses, and because of less frequent regeneration of the DPF. There will be additional benefits in terms of overall energy consumption and GHG emission reduction from fuels manufacture if the fuels used are less processed than conventional diesel or gasoline.

3.2.2. Fuel requirements of GCI engines

The fuel used need not have high RON, and low-octane components such as naphtha, which are expected to be abundant in the future, could be used to make the fuel without much additional processing in the refinery. A high RON makes it difficult to ensure and control combustion at very low loads; however, if the RON is too low, combustion will be more similar to combustion with diesel fuel, and the simultaneous control of NO_x and soot will become difficult at a higher load. The optimum fuel has been suggested to have a RON between 75 and 85, based on tests performed in a small single-cylinder engine with a compression ratio of 16 in Ref. [51]. The optimum RON was considered to be in the "range of 70" for GCI, based on experiments in a heavy-duty CI engine [39].

If the ID or RON is high enough, low-soot and low-NO_x operation is possible even if the fuel contains relatively involatile components in the diesel boiling range [36,52]. Fuels of very wide volatility, such as mixtures of diesel and gasoline, presumably enable more stratification of the fuel and in fact extend the GCI operating range [53]. This relaxed volatility requirement could make refinery operations more flexible by enabling heavier diesel components to be blended with gasoline components in order to make GCI fuel, as long as considerations that affect safety, such as flash point requirements, are addressed. However, if the concentration of components in the diesel boiling range is less than 50% by volume, there is little impact on the flash point and flammability of such blends [57,58]. Gasoline/diesel blends for GCI are likely to require 25% or less of components in the diesel boiling range and should be as safe as current market gasolines [57,58]. Compared with conventional gasoline, low-octane gasolines will have a lower carbon footprint due to lower energy use in their manufacture and higher hydrogen/carbon (H/C) ratios, because they will be more paraffinic. On a well-to-wheel basis, compared with an equivalent SI engine running on a gasoline of much higher RON, a GCI engine running on 70 RON fuel could have a GHG footprint that is lower by around 30% [49,50]; the GHG impact of such an engine would be around 5% lower than that of an equivalent diesel engine, with the benefit coming from fuel manufacture.

3.2.3. Challenges and development work needed

There has been a great deal of research on this topic during the past decade; the concept has been well-demonstrated and the challenges have been identified. Development work is essential to implement GCI technology in practical vehicles. Work would be needed on cold start and idle, acceptable transient operation, adequate emissions control (particularly of HC and CO), stability at low load, and control of the pressure rise rate/noise at high and medium loads. Hardware developments to optimize the combustion chamber, EGR system, injectors, turbocharger/supercharger, after-treatment system, and injection strategy will be needed to meet the required targets for emissions, efficiency, noise, and stability. This optimization should ideally be for a fixed fuel of known RON and volatility characteristics; however, given adequate control, the engine could be made to be tolerant to minor changes in fuel properties. Current developments in GCI [24,25,46] use market gasolines; as discussed above, however, the use of low-octane gasoline of around 70 RON would bring further advantages. Such a fuel needs to be more fully specified in terms of volatility and composition, as was done in Refs. [10,11], in order to enable its practical manufacture. The fuel should have adequate lubricity to protect the injection system and sufficient detergency to keep the injection system clean; appropriate fuel additives will need to be used. One way to provide sufficient lubricity might be to add a few percentages of a biodiesel such as fatty acid methyl ester (FAME) to the fuel blend.

The development effort does not require any entirely new technology; rather, it needs the adaptation of existing technology. Such adaptation would actually simplify existing diesel technology by resulting in, for example, simpler after-treatment systems and lower injection pressures. The challenges in developing GCI may compare favorably with the challenges that were encountered in the development that has already been achieved to meet NO_x and particulate standards in diesel engines while using diesel fuel.

GCI can be considered either as a way to reduce the cost of CI (currently diesel) engines without compromising on efficiency, or as a way to increase the efficiency of an engine carrying a gasoline fuel by running it in CI mode rather than in SI mode. If low-octane gasoline is used, fuel manufacture will use less energy and will have a lower GHG footprint in comparison with the manufacture of today's gasoline and diesel.

3.2.4. Outlook for GCI engines

GCI offers the prospect of diesel-like efficiency while running on a gasoline with much lower octane (~70 RON) than today's market gasolines; it might also need a cheaper engine and after-treatment system. Such low-octane gasoline fuels could be made without much further processing of low-octane gasoline components, which are expected to be readily available because the demand for heavier fuels such as diesel and jet fuel is expected to increase faster than the demand for conventional high-octane gasoline. Thus, GCI presents benefits both from the engine and the fuel side. In addition, GCI provides a possible opportunity to mitigate the consequences of the demand imbalance between gasoline and middle distillates that is expected in the future.

Engine manufacturers have a large stake in existing diesel engine technology using diesel fuels. Therefore, in the short term—say up to 2025—diesel fuel (CN > 40) will continue to be used in CI engines. However, if diesel fuel continues to be used, the cost of these engines is likely to increase in order to allow the engines to meet the increasingly stringent emissions standards for NO_x and soot. There is a possibility that low-octane gasoline components may become significantly cheaper than low-sulfur diesel fuel, and may drive the development of GCI engines. In addition, the current demonization of diesel, with plans to ban diesel engines, may provide a better political climate to enable the acceptance of GCI, which uses a fuel that can be classified as “gasoline.”

Collaboration between many stakeholders, such as policy makers and the oil and auto industries, will be required to enable the deployment of a new fuel/engine system such as GCI. Such collaboration could be more likely in countries in which the alignment of stakeholders is easier (e.g., perhaps in China), in countries where the commitment to existing diesel technology is relatively weak, or when low-octane gasoline is significantly cheaper than low-sulfur diesel as the expected demand imbalance between middle distillates and gasoline starts to take hold.

GCI engines will have to use existing market fuels to start with. A possible fuel for GCI could be gasoline/diesel mixtures (i.e., dieseline) [59] with a lower octane number than market gasoline, although systems running on market gasoline are being developed [24,46].

A GCI engine is well-suited to be part of a parallel hybrid powertrain, with the GCI engine working in a suitable narrow operating range. It could also be run mostly at a fixed operating condition to charge the battery in a series hybrid. The deployment of GCI engines could be made easier by making them insensitive to fuel autoignition quality through combustion phasing control using cylinder-pressure-based control systems. This would make it easier for GCI engines to shift from conventional fuels to low-octane gasoline. It is less desirable to continue to use market gasoline or mixtures of gasoline and diesel in GCI, since both gasoline and diesel would be “downgraded” in the vehicle after being “upgraded” in the refinery. Low-octane gasoline will need less energy to produce and will help to further reduce the overall GHG impact. CI engines could run on low-octane gasoline (RON in the range of 70–85) with relaxed volatility constraints in the long term—say after 2030. The transition to the long-term scenario will depend on many factors, including the development strategies employed by the original equipment manufacturers (OEMs). New engine concepts such as the Achates opposed piston engine might be easily adapted to run on GCI concepts [60]. The Delphi GDCI [24,46] and the Mazda SkyAktiv [25] follow GCI principles but use market gasolines.

3.3. Reactivity-controlled compression ignition

The requirement for fuel autoignition quality or ID in GCI engines varies with pressure and temperature in the engine. For example, under low loads when autoignition is difficult, a low ID will be beneficial, whereas under high loads when soot formation is a problem, high ID in the fuel would be desirable. RCCI is one way to meet the requirement of varying ID under different operating conditions [61–65]. In the RCCI concept, a fuel with a high ID such as a market gasoline or ethanol [61,62], or natural gas [63], is injected in the port; ignition is then triggered by the direct injection of a fuel such as commercially available diesel fuel, with low ID, near the top dead center. Depending on the engine operating conditions, the ratio of the two fuels used is changed; for example, relatively more diesel fuel is used when autoignition is difficult, as under low loads. However, the amount of diesel fuel used is around 10% of the total fuel used over a normal operating cycle. Widespread adoption of RCCI in heavy-duty engines should help to moderate the expected increase in demand for diesel fuel. RCCI could also be implemented using one fuel—a market gasoline—on board but reducing its ID by using varying amounts of a diesel ignition improver and by injecting this reactive fuel, rather than diesel fuel, to trigger ignition [64]. RCCI combustion can have a very high indicated efficiency, near zero levels of NO_x and soot, and acceptable pressure rise rate and noise over a wide range of engine loads [65]. RCCI requires two fuel injection systems, which will increase the cost and complexity. Heavy-duty engines are already more expensive, and the incremental cost will be smaller in percentage terms. The chances of misfueling could also be reduced in fleet operations with centralized fuel provision. Hence RCCI is probably better suited for commercial fleet operations.

3.4. Octane on demand

In SI engines, high octane is usually needed only in a small fraction of the engine’s operating region [66–71]. Octane on demand (OOD) makes the best use of available fuel octane quality. The engine carries a high- and low-octane fuel, and has two fuel injection systems. These components can come from separation of the single gasoline currently available at the pump [66,67], or can be separately sourced and stored on the vehicle [68]. Such an approach allows the engine to be redesigned (e.g., with a higher compression ratio) to improve efficiency [66,67]. Alternatively, with the same compression ratio, the engine can use high-octane fuel only part of the time when it is needed, and use low-octane fuel for most of the operating regime. Since low-octane fuel has a lower carbon footprint, there will be an overall reduction in GHGs on a well-to-wheel basis, even if the engine compression ratio is not increased [70,71].

3.5. Longer term approaches to reduce overall GHG: Electrofuels

Electrofuels, or e-fuels, can be hydrocarbons—liquid or otherwise—made with CO_2 and hydrogen, or hydrogen itself. E-fuels have a very low GHG footprint if they are made using renewable or nuclear energy. Hydrogen can be made from the electrolysis of water and can be used in fuel cells. However, the production of e-fuels is very energy intensive, and the well-to-wheel efficiency of e-fuels is very low. In one study, the well-to-wheel efficiency for a passenger car was estimated to be 13% for the e-fuel route in comparison with 73% for a BEV approach [72]. Hence, if sufficient renewable electricity is available, it is far more efficient to use it to power BEVs than to use it to make e-fuels. E-fuels would make commercial sense only if the carbon price was very high. Moreover, e-fuels could only a supply a very small fraction of the energy requirement of the global vehicle fleet on any realistic timescale [72,73]. For example, for the European Union (EU) to power its road transport using e-fuels, the EU would require one and a half times more energy than its current total electricity production, and all of this additional electricity would have to be renewable. If renewable electricity is available at all for such a purpose, the focus should be on e-fuels for aviation, which cannot be realistically powered by batteries [8].

More and more electricity will be produced when it is not needed as the share of solar and wind electricity in electricity generation increases, because of the intermittent nature of renewables. This excess electricity could be used to reduce the GHG footprint of the aviation sector to a certain extent by making aviation e-fuels.

4. Conclusions

Although there may be regional variations, the following conclusions are relevant to global transport, the growth of which is set to be dominated in future by non-OECD countries such as India and China.

- The demand for transport energy is very large and growing. Transport will continue to be primarily powered by ICEs using petroleum-based fuels for decades to come because alternatives start from a low base and face significant barriers to unrestrained growth. There will be severe environmental, economic, and social consequences that may be unsustainable if premature changes are forced onto the existing system.
- It is absolutely essential that the efficiency and environmental impact of ICEs be improved in order to maintain/improve the sustainability of the transport sector.
- The global demand for diesel and jet fuel (middle distillates) is expected to increase faster than the demand for gasoline. The availability of low-octane gasoline components (i.e., naphtha) is likely to increase as more oil is processed to meet the increased demand for middle distillates. Future engines should use fuel components such as naphtha, which are likely to be more easily available and may be cheaper than diesel, to maintain the sustainability of fuels manufacture while bringing benefits to consumers.
- Significant improvements are possible using existing market fuels via improved combustion, control, and after-treatment systems, assisted by partial electrification in the form of hybridization and weight reduction through the use of light materials. For example, efficiencies could be improved by 50% in comparison with the current US average for SI engines, and pollutants such as particulates and NO_x from diesel engines could be reduced to negligible levels through the use of better catalysts and intelligent management of temperatures and combustion modes. These improvements might also require changes in fuels. For example, sulfur levels must decrease in many markets where they are high, in order to enable more efficient after-treatment. Fuel anti-knock quality may need to increase to enable higher efficiency in SI engines, but any possible benefits would need to be assessed on a life-cycle basis. In many areas, specifications assume that a higher MON is better for fuel anti-knock quality. Such specifications need to be changed to bring them in line with the requirements of efficient modern engines.
- There is greater scope for improvements if engines are not constrained to use current market fuels; new fuel/engine systems could be developed to additionally leverage benefits in fuels manufacture and to use fuel components that might be readily available.
- A very good example of a beneficial future fuel/engine system is GCI using low-octane gasoline. GCI makes it easier to reduce emissions of NO_x and particulates, while enabling diesel-like efficiency. It also uses fuel components that may be in surplus in the future, and hence may be cheaper. RCCI and OOD could use existing market fuels, but could also use low-octane gasoline in the future.
- Eliminating GHGs completely from the transport sector will require massive—perhaps unsustainable—investments in renewable electricity generation along with the use of this electricity to make e-fuels such as hydrogen. However, this route is very energy intensive. If enough renewable electricity is available, it might be best used to drive electric vehicles; however, this would generate its own environmental problems associated with battery manufacture and would pose huge challenges in regard to the charging infrastructure. Nevertheless, as the share of renewables in the power sector increases, more unwanted electricity will be available due to the intermittent nature of wind and solar power. Such excess energy could be used to make e-fuels in order to reduce the GHG impact of aviation, which will continue to rely on combustion engines for the foreseeable future.

Nomenclature

ASTM	American Society of Testing and Materials
BEV	battery electric vehicle
CFR	Cooperative Fuels Research
CI	compression ignition
CN	cetane number
CO	carbon monoxide
CO_2	carbon dioxide
DCN	derived cetane number
DPF	diesel particulate filter
EGR	exhaust gas recirculation
EOI	end of injection
EU	European Union
FAME	fatty acid methyl ester
FSN	filter smoke number
GCI	gasoline compression ignition
GDCI	gasoline direct-injection compression ignition
GHG	greenhouse gas
GPF	gasoline particulate filter
HC	unburned hydrocarbons
HCCI	homogeneous charge compression ignition
ICE	internal combustion engine
ID	ignition delay
IDW	ignition dwell
LDV	light-duty vehicle
LPG	liquid petroleum gas
MON	motor octane number
MTBE	methyl tertiary butyl ether
NO_x	nitrogen oxides
OECD	Organization for Economic Co-operation and Development
OOD	octane on demand
PCI	premixed compression ignition
PM	particulate matter
PPC	partially premixed compression
PRF	primary reference fuel
RCCI	reactivity-controlled compression ignition
RON	research octane number
S	sensitivity
SI	spark ignition
SOC	start of combustion
SOI	start of injection
SRG	straight run gasoline
TN	toluene number
TRF	toluene reference fuel

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