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The scope for improving the efficiency and environmental impact of internal combustion engines

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ABSTRACT

Currently 99.8% of global transport is powered by internal combustion engines (ICEs) and 95% of transport energy comes from liquid fuels made from petroleum. Many alternatives including battery electric vehicles (BEVs) and other fuels like biofuels and hydrogen are being considered. However, all these alternatives start from a very low base and face very significant barriers to unlimited expansion so that 85–90% of transport energy is expected to come from conventional liquid fuels powering combustion engines even by 2040. Hence it is imperative that ICEs are improved in order to reduce the local and global environmental impact of transport. This paper considers the scope for such improvement after discussing the basic principles that govern engine efficiency and the technologies to control exhaust pollution. The great scope for such improvement is illustrated by considering various practical approaches already in the market. For instance, the best in class SI engines in the U.S. have 14% lower fuel consumption compared to the average. Engine and conventional powertrain developments alone could reduce the fuel consumption by over 30% for light duty vehicles (LDVs). Implementing other technologies such as hybridisation and light-weighting could reduce fuel consumption by 50% compared to the current average for LDVs. Current after-treatment technology can ensure that the exhaust pollutant levels meet the most stringent current emissions requirements. Indeed, with the most modern diesel vehicles, the exhaust can be cleaner than the intake air in urban centres. The implications for transport policy, particularly where there are plans to ban ICEs, are considered in the final discussion. All available technologies need to be deployed to mitigate the environmental impact of transport and it would be extremely short-sighted to discourage further development of ICEs by limiting their sales.

1. Introduction

Transport of goods and people contributes around 25% of global CO_2 emissions from fossil fuel combustion [1]. However, its share of global greenhouse gas (GHG) emissions including other contributors such as methane is around 14% [2, 3], comparable to the share from livestock farming [4]. The world had an estimated 1.1 billion light duty vehicles (LDV), defined as those weighing less than 8500 lb (3860 kg) and around 380 million heavy goods vehicles (HGV) in 2015 [5]; in 2018 the global production of LDVs was around 70 million and that of commercial vehicles, around 25 million [6]. The number of vehicles is increasing, primarily in developing countries, and by 2040 the number of LDVs in

Abbreviations: ASTM, American Society of Testing and Materials; BEV, battery electric vehicle; CAD, crank angle degrees; CFD, computational fluid dynamics; CFR, cooperative fuels research; CI, compression ignition; CO, carbon monoxide; DCN, derived cetane number; DPF, diesel particulate filter; EGR, exhaust gas recirculation; EOI, end of injection (CAD); EU, European Union; FSN, filter smoke number; GCI, gasoline compression ignition; GHG, greenhouse gas; GPF, gasoline particulate filter; HC, hydrocarbons; HCCI, homogeneous charge compression ignition; HEV, hybrid electric vehicles; ICE, internal combustion engine; ID, ignition delay (SOC-SOI); IDW, ignition dwell (SOC-EOI); LPG, liquid petroleum gas; MBT, maximum brake torque; MFB, mass fraction burned; MON, motor octane number; NO_x, nitrogen oxides; OOD, octane on demand; PPC, partially premixed compression; RCCI, reactivity controlled CI; RDE, real driving emissions; RON, research octane number; S, sensitivity (RON-MON); SCR, selective catalytic reduction; SI, spark ignition; SOC, start of combustion (CAD); SOI, start of injection (CAD); SRG, straight run gasoline; TWC, three way catalyst; AFR, air fuel ratio; AKI, anti knock index; ASC, ammonia slip catalyst; BOE, barrel of oil equivalent; CN, cetane number; CNG, compressed natural gas; DEF, diesel exhaust fluid; DME, dimethyl ether; DOC, diesel oxidation catalyst; GDI, gasoline direct injection; LDV, light duty vehicle; LNG, liquid natural gas; LNT, lean NOx trap; MTBE, methyl tert-butyl ether; NEDC, new european drive cycle; RFO, residual fuel oil; PEMS, portable emissions measurement system; PFI, port fuel injection; PHEV, plugin hybrid electric vehicle; PM, particulate matter; PMEP, pumping mean effective pressure; PRF, primary reference fuel; TN, toluene number; TRF, toluene reference fuel; UHC, unburned hydrocarbons; WLTP, worldwide light duty test procedures.

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Table 1
Percentage share of global transport energy demand in 2018 across different transport sectors [10].

Passenger Sector	
Light duty vehicles (LDV)	44%
Rail, buses and 2-3 wheelers	7%
Aircraft	10%
Freight transport	
Heavy duty road	26%
Marine	8%
Rail and pipeline	5%

the world is expected to increase to 1.7 to 2 billion [5, 7-10]. Currently transport is almost entirely (> 99.8%) powered by combustion engines – land and marine transport runs on reciprocating internal combustion engines (ICEs) while air transport is dominated by jet engines. Combustion engines also fulfil important roles in industry and power generation.

Liquid fuels have become the energy source of choice for transport because of their high energy density and because they are easy to transport and store. For instance, at normal temperatures and pressure, the volumetric energy density of gasoline is around 3100 times and 800 times higher compared to hydrogen and natural gas, respectively. A vast global infrastructure for the manufacture and distribution of liquid fuels which will be expensive and difficult to replace or replicate has been established over the past century or so. Transport and petroleum (crude oil) are very closely linked – currently around 95% transport energy is provided by liquid fuels made from petroleum and around 60% of crude oil is used to make transport fuels [7-10].

Table 1 shows the share in demand of transport energy across different transport sectors – it is to be noted that aircraft and land and marine freight transport account for 50% of global transport energy demand [10]. Around 80% of global LDVs are powered by spark-ignition (SI) engines using gasoline [8] while the freight sector is dominated by compression ignition (CI) engines running on diesel fuel. Marine transport mostly uses residual fuel oil (RFO) though a large fraction of RFO is also used for domestic and industrial heating.

The global demand for transport energy is large - Table 2 shows the average daily demand for transport fuels for the third quarter of 2018 [11]. The first column shows the demand in barrels of oil equivalent (BOE). An exajoule (10^{18} Joule) is equivalent to 163.4 million BOE and assuming a volumetric energy density of 32.5 MJ/l for gasoline, 36 MJ/l for diesel and jet fuel and 40 MJ/l for residual fuel oil, the fuel volumes used are shown in the last column. Thus, the world uses, on average, over 11 billion litres of gasoline, diesel and jet fuel *daily*. This demand is growing with the growth expected to occur almost entirely in developing (non-OECD) economies and is expected to be around 40% higher in 2040 compared to 2015 [7-10]. The demand for energy for freight transport and aviation is expected to grow faster than for lighter vehicles because of the greater opportunity for improving fuel efficiency and for electrification in the light duty sector [7, 9]. Hence the demand for diesel and jet fuel (middle distillates) is expected to grow faster than for gasoline [7, 9].

Currently there are many initiatives across the world to develop alternatives to ICEs and petroleum-based conventional fuels driven by concerns about climate change and local air quality associated with transport because of emissions of CO_2, particulates, nitrogen oxides (NO_x), carbon monoxide (CO) and hydrocarbons (HC). Indeed, criticism of ICEs is common in the news media and amongst some politicians in many countries and has led to a belief that the elimination of ICEs is desirable and imminent. Of course, transport policy is also influenced greatly in many countries by the desire for economic growth, energy independence and energy security. The ICE could be replaced by a battery or a fuel cell while the alternatives to conventional fuels include biofuels, natural gas, hydrogen, synthetic fuels, electro-fuels, liquid petroleum gas (LPG) and methanol [12, 13].

However, all these alternatives start from a very low base and face significant barriers to rapid and unrestrained growth. Such alternatives need to be assessed on the basis of life-cycle analysis and there will be severe environmental, economic and social consequences if alternatives are imposed prematurely [12]. For instance, there is great current interest in electrification of transport but there are different degrees of electrification and the need for an ICE is only eliminated by a battery electric vehicle (BEV). However, the GHG impact of BEVs could be worse compared to conventional vehicles if the electricity generation and the energy used in battery manufacture, which depends on battery capacity and can be large, is not sufficiently decarbonised. In many growing economies such as China and India coal will play a substantial role in power generation for decades to come and the carbon intensity of power generation will be too high for BEVs to be beneficial from a GHG consideration. Indeed, in such countries, even emissions of particulates, NO_x and sulfur dioxide (SO_2) will be worse for BEVs though they will be displaced away from the vehicle. In several other countries, despite significant increases in renewable power generation, the dispatchable power needed to meet demand during EV charging periods will today largely be met with generating capacity powered by natural gas. When this electricity is generated from gas turbines, GHG emissions from BEVs are comparable to emissions from current ICE-powered vehicles.

In addition, there are very significant human toxicity implications associated with the mining of metals needed in batteries [12] which cannot be ignored as the number of BEVs grows. Large engines in commercial transport and aircraft cannot be run on batteries because of the size of the batteries required [12]. At the end of 2018, the world had around 3.3 million BEVs [14]; in 2019 around 2.3 million BEVs and plugin hybrid electric vehicles (PHEVs) were sold, of which around 70%,were BEVs, (giving a total of approximately 4.9 million global BEVs at the end of 2019) [15, 16]. More than half of them were sold in China [15, 16] which would actually have worsened the global GHG impact of transport. Indeed, policy on BEVs in China is being driven by the need to gain a technological lead in “new energy vehicles” and concerns about urban air quality rather than GHG considerations. So by the end of 2019 global sales of BEVs amounted to around 2.5% of global LDV sales and the global stock of BEVs was just under 0.4% of total LDV numbers. A hundred-fold increase by 2040 in BEV numbers, compared to 2019, would bring their number to around 490 million, roughly 29% of global LDV numbers which would account for around 13% of transport energy since LDVs use around 44% of transport energy (Table 1). Even under the unrealistic assumption that all these 490 million BEVs were made with carbon-neutral energy and run on carbon-free electricity, at best around 13% of transport-related GHG would be saved by such an enormous increase in BEV numbers. In any case, such a massive increase in BEV numbers will require very large prior investments in charging infrastructure, additional electricity generation, financial incentives to encourage the sale of BEVs and recycling of batteries [12] which may not be affordable in most countries. The supply and cost of metals needed, particularly of cobalt, to support such a large spread of BEVs could also be very challenging. Similarly, any increase in the share of biofuels, hydrogen or other energy sources for transport will face significant challenges [12]. Hence most credible projections suggest that even by 2040, 85-90% of transport energy will still come petroleum based liquid fuels [7, 10, 17].

Thus, for decades to come, global transport will be predominantly powered by ICEs using petroleum-based fuels. It is imperative that the efficiency and environmental impact of such engines are improved in order to bring about any significant and realistic improvement in the sustainability of transport. In fact, there is great scope to bring about such improvements in the short term with better combustion, after-treatment and control systems and in the medium term with the development of new fuel/engine systems. The vast existing transport infrastructure can be used to support such initiatives without requiring too much change or investment. This paper discusses the scope for such improvements, particularly for the short and medium term. In the long term, as the

Table 2
Average global daily demand for transport fuels, third quarter 2018 [11].

Assuming 32.5 MJ/l for gasoline, 36 MJ/l for diesel and jet fuel, 40 MJ/l for RFO. 1 exa joule = 163.4 million barrels of oil equivalent (BOE)			
Total	Million barrels of oil equivalent (BOE)	Energy, exajoules	Fuel Volume, billion litres
Gasoline	26.4	0.162	4.985
Diesel/Gasoil	28.1	0.172	4.778
Jet/Kerosene	8.0	0.049	1.361
Residual Fuel Oil (RFO)	7.0	0.043	1.075
Other*	30.0		
Total	99.6		

* Includes naphtha, LPG, ethane, other petrochemicals and energy use in refineries.

overall energy system transforms and the share of renewable energy increases and battery and fuel-cell technology improve, other alternatives become increasingly practical. However first we briefly consider the existing engines and fuels and the mechanisms that limit efficiency and affect emissions.

2. Current IC engine combustion systems and fuels

Several books [18-21] discuss engine combustion systems and fuels and this section contains a brief summary.

2.1. Engine combustion systems

Land and marine transport are powered by two major engine combustion systems.

Most light duty engines run on spark Ignition (SI) engines and use gasoline fuel. Combustion is initiated in a SI engine by an electric spark and fuel energy is released as a flame propagates through a mixture of fuel and air that is compressed after premixing. In modern SI engines operated at lambda = 1 (stoichiometric), CO, HC and NO_x emissions in the exhaust are reduced to acceptably low levels through the use of a three-way catalyst. The numbers of nanoparticles (less than 100 nm in diameter) are of increasing concern though particulate mass is very low in the exhaust of a SI engine. Gasoline particulate filters (GPFs) are likely to be required in the future to tackle these particulate emissions. SI engined vehicles on average convert only 20-25% of fuel energy to motive power mainly because of the requirement of throttling at low loads and knock [18, 19] at high loads – the principles are discussed in greater detail in Section 3. However, their impact on pollution and air quality is low because of the use of effective after-treatment. Larger SI engines, such as those required for commercial vehicles, also have to run at low speeds, would be more prone to knock on a given fuel because there is more time available for chemical reactions leading to knock and their efficiency would be reduced. Hence, SI engines are not usually used in commercial transport requiring large engines.

In compression ignition (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. Currently all practical CI engines use diesel fuel – they are diesel engines. Soot (particulates) and NO_x emissions are a significant problem for diesel engines. Technology such as complex after-treatment and high-pressure injection systems are needed to control them. Hence modern diesel engines are much more expensive compared to SI engines of similar size but are more efficient compared to SI engines.

There has been much recent interest in homogeneous charge compression ignition (HCCI) combustion. In a HCCI engine, fuel and air are fully premixed as in a SI engine but heat release occurs by autoignition as in knock in a SI engine. The thermal efficiency of HCCI engines is very high but they are constrained to operate at lean mixture strengths and hence, low loads, 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. HCCI engines are not practical for this reason and also because they are difficult to control. HCCI-like combustion with low NO_x and soot and high efficiency but which is easier to control can be ensured by not fully premixing fuel and air. Such 'premixed-enough' combustion systems are discussed in Section 5.

2.2. IC engine fuels

Gasolines need to have high anti-knock quality as specified by RON and MON, the Research and Motor Octane Numbers or the Anti-Knock Index (AKI = (RON + MON)/2)) [20, 22]. Most market gasolines have RON > 90 and a MON value about 10 lower than the RON value. Fuel requirements of SI engines are discussed in greater detail in [23]. For diesel fuels, autoignition quality is measured by the Cetane Number, CN. Diesel fuels generally need to have 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 [20, 22]. The cetane number of jet fuel is lower than that of conventional diesel fuel and it is blended using more volatile components than are found in the diesel boiling range. Marine transport fuels are blended from the heaviest components in the fuel pool and have a high sulfur content. Marine engines could be forced to run on conventional diesel fuel because of current moves to reduce the sulfur content of marine fuels, further contributing to the increase in demand for conventional diesel fuel in the future.

Gasoline-like fuels are defined in this paper as fuels with CN < 30 or RON > 60, i.e., in the gasoline autoignition range as in [22].

The first step in the manufacture of practical transport fuels is the distillation of crude oil. Gases dissolved in the crude oil are released when oil is heated above ambient temperature and make up Liquid Petroleum Gas (LPG). Up to 2% of the crude could be LPG which consists mostly of propane and some butane. The fraction in the gasoline boiling range, with boiling points between ~20 °C 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 in the range of ~160 °C to ~380 °C. Heavy components, with boiling points higher than 380°C, could constitute 40%–60% of the weight of petroleum depending on the source of the crude oil. In the refinery, these heavy components are first "cracked" into smaller molecules which are further processed to produce useful products e.g., by reducing sulfur or by 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" which 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 like methyl tertiary butyl ether (MTBE) are blended with refinery components along with some fuel additives to meet the required fuel specifications [20, 21].

3. Engine and vehicle efficiency – main principles

3.1. Introduction

It has long been known that high compression ratios and weak, or fuel-lean, mixtures improve the efficiency of SI engines, but since 1980 SI engines have invariably been constrained to operate with stoichio-

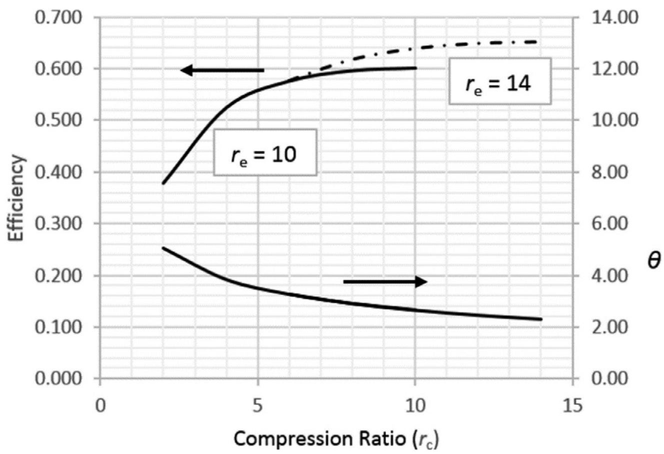

Fig. 3.1. Plot of efficiency (Eq. 3.1) and the temperature rise ratio (θ) during heat addition, with a temperature rise from combustion of 2000 K, the ratio of heat capacities of 1.4, and an initial temperature of 300 K – the solid lines are for an expansion ratio of 10, the dashed for an expansion ratio of 14.

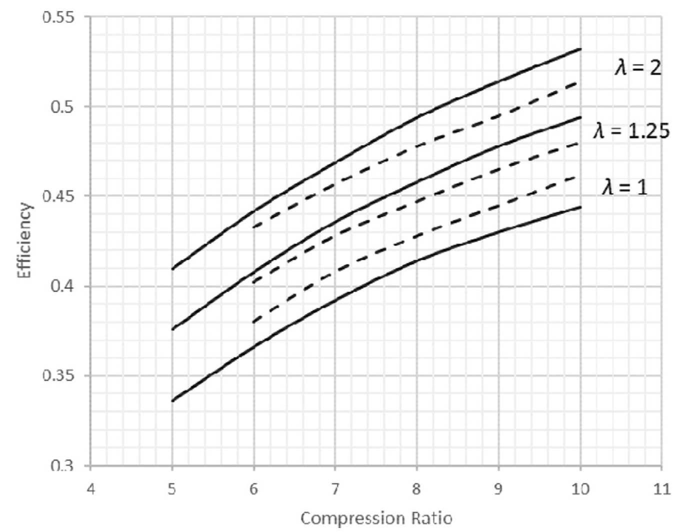

Fig. 3.2. Fuel-Air Cycle efficiency as a function of compression ratio and mixture strength - solid lines, Tizard and Pye [24]; broken lines, Taylor [25] (the Taylor data does not include the effects of dissociation so overestimates the efficiency of the stoichiometric mixture).

metric mixtures so that three-way catalysts can virtually eliminate unwanted emissions. With weak mixtures the catalytic oxidation of carbon monoxide (CO) and unburned hydrocarbons (UHC) is straightforward; the challenge is the elimination of nitrogen oxides (NO_x, a mixture of NO and NO_2) as a chemically-reducing environment is needed. If the mixture is sufficiently weak, then combustion temperatures will be too low to form NO_x, but to meet current emissions regulations these mixtures would not necessarily be flammable in a conventional engine. In the late 1990s lean-NO_x traps (LNT) were introduced and these use materials such as barium carbonate to react with the NO_x. However, regeneration is needed to convert the barium nitrate back to barium carbonate during rich mixture excursions. In any case the trapping efficiency was only about 50%, and as emissions legislation became more demanding these technologies were no longer adequate and lean burn operation had to be again abandoned. The challenge of reducing NO_x emissions in an overall weak mixture is also applicable to diesel engines and this has led to Selective Catalytic Reduction (SCR) that uses an aqueous urea solution (32.5% by mass of $C(NH_2)_2O$) to generate ammonia (NH_3) that reduces about 90% of the NO_x. Such systems have become widely used in diesel engines since 2010 and could be readily applied to SI engines. More information on these technologies and their development can be found in texts such as Heywood [18] and Stone [19], with some of the more recent trends discussed later in Sections 4.1 and 4.2

It is also well known that combustion needs to be rapid (so as to emulate the instantaneous heat addition of the so-called Otto cycle analysis) and repeatable (if there are cycle-by-cycle variations in combustion, then ignition can only be optimised for the mean cycles). The key loss that needs to be eliminated is from throttling, since this means of reducing the air flow increases the pumping work loss. Options for this include cylinder de-activation, control of the piston stroke (as in the original Atkinson engine) or closing the inlet valve mid-stroke of the piston (as originally proposed by Miller for limiting the maximum cylinder pressure in diesel engines). Whether inlet valve closure is early or late the theoretical performance is the same and has the result of reducing the effective compression ratio. However, an air standard cycle model [19] can be used to show that the expansion ratio (r_e) is much more important than the compression ratio (r_c):

$$\eta = 1 - \frac{\theta r_c + r_c^{\gamma} - r_e^{\gamma} + \gamma(r_e - r_c) \times r_e^{\gamma-1}}{\theta r_c r_e^{\gamma-1}} \tag{3.1}$$

where: γ is the ratio of heat capacities and θ is the ratio of temperature rise during heat addition to the temperature at the end of compression.

The significance of Eq. 3.1 is shown in Fig. 3.1 where it has been assumed that the temperature rise associated with combustion is 2000 K and the ratio of heat capacities is held at 1.4 with an initial temperature of 300 K. If the compression ratio is half of the expansion ratio then the loss of efficiency will only be a couple of per cent (noting that the air standard cycle analysis predicts almost double that which might be achieved) and this compares with a reduction in pumping mean effective pressure (PMEP) of order 0.5 bar that might represent almost 10% of the output of the engine. Air standard cycle analyses ignore the real thermodynamic performance of the air fuel mixture and combustion products and dissociation. The importance of these is discussed in Section 3.2.

A simpler way of reducing the pumping loss that can be applied with three-way catalysts is to employ Exhaust Gas Recirculation. Up to 25% is viable (and it makes little difference whether this is defined on a volumetric, gravimetric or molar basis), and this could lead to a reduction in PMEP of about 0.25 bar. However, EGR will slow combustion and increase the level of cycle-by-cycle variations in combustion, so mitigation by increasing in-cylinder motion is important.

Another strategy to reduce part load losses is to 'downsize' the engine; this means supercharging the engine (either directly or with an exhaust powered turbine) so that a reference operating torque on the road-load curve corresponds to the engine operating at a higher engine load than it would with the intake at ambient pressure. However, this is almost certainly associated with a reduction in compression ratio so as to avoid combustion knock at full load and this imposes an efficiency penalty across the whole operating envelope.

It is of course much better if part load operation is eliminated and this is possible with hybrid engine vehicles (most simply but not efficiently with a series hybrid) or to a large extent with shunt transmission systems, and these are discussed in Section 3.4.

3.2. Real thermodynamic behaviour of combusting mixtures

The air standard Otto cycle analysis uses the properties of air at ambient conditions and an idealised heat input. Tizard and Pye [24] were the first to consider the real heat capacity of the reactants and products and the significance of dissociation. Fig. 3.2 shows their computation of Fuel-Air cycle efficiency for weak mixtures, including the effects of dissociation. Also included in Fig. 3.2 are the results of the Fuel-Air cycle calculations reported by Taylor [25], with perhaps not surprisingly

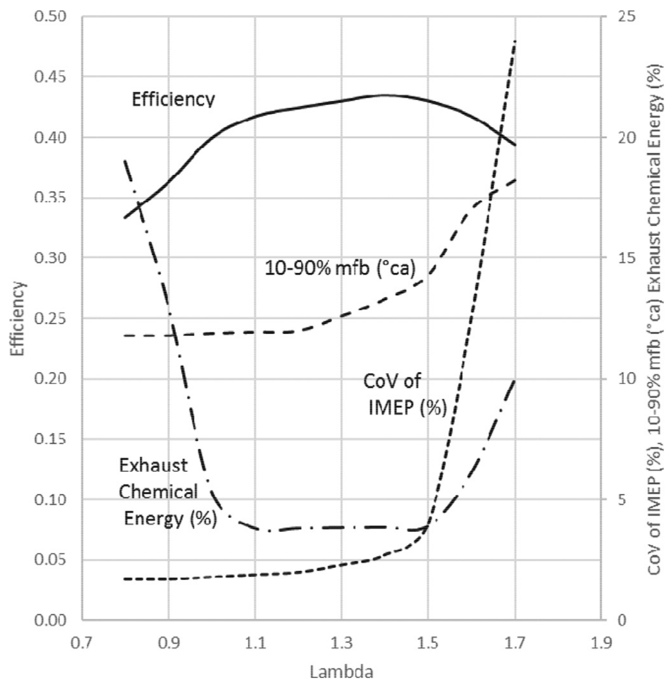

Fig. 3.3. Experimental measurements of a natural gas fuelled engine with a fast burn combustion system operating at 1500 rpm and a 13:1 compression ratio with MBT ignition timing [27]. The exhaust chemical energy is expressed as a percentage of the input fuel energy.

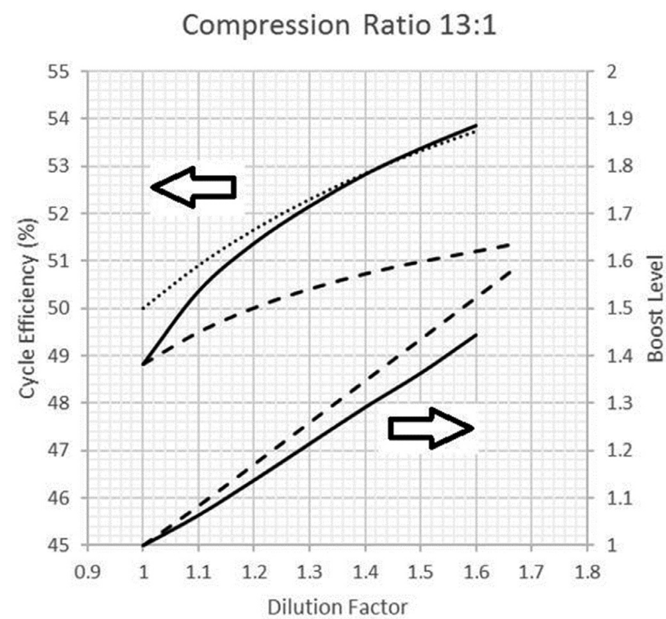

Fig. 3.4. The effect of dilution by air (solid line) and EGR (broken line) on the cycle efficiency and boost requirement for a fixed load. As with the fuel-air cycle efficiency calculations the assumptions are for adiabatic and reversible compression and expansion, with instantaneous heat input at top dead centre. The Taylor [25] prediction for efficiency (dotted line) does not include the effect of dissociation.

significant differences, not least since the Taylor data have not included the effects of dissociation. Pye [26] subsequently noted that in the 1920s there was very limited data on the high temperature heat capacity of gases and equilibrium constants, but even in the 1930s [26] the values of the equilibrium constants do not agree well with current values. None the less, this early work explained why the observed indicated efficiencies were much lower than predicted by the Otto cycle analysis and why maximum power occurs rich of stoichiometric, and why weak mixtures give a higher indicated efficiency. Another way of quantifying the impact of dissociation is to calculate the calorific value of the carbon monoxide and hydrogen in the exhaust of an engine operating with stoichiometric combustion – this energy content amounts to 3-4% of the fuel calorific value.

So, weakening the mixture increases the ideal cycle efficiency, but as Fig. 3.3 shows there are competing factors that will reduce the efficiency, namely an increase in the level of cycle-by-cycle variations in combustion, an increase in the emissions of partially burned fuel, and an increase in the duration of the main combustion period. In a naturally aspirated engine operating at full load there would be a reduction in the mechanical efficiency as the mixture is weakened since the lower output makes the mechanical losses more significant. However, if the engine is supercharged (perhaps driven by an exhaust turbine) then the output can be maintained, and to a first order the boost pressure ratio will need to equal the lambda (for example a boost pressure ratio of 1.4 for a lambda of 1.4), as will be seen later in Fig. 3.4.

As soon as lambda 1.1 is reached there will be negligible carbon monoxide in the exhaust and the efficiency increases until lambda reaches 1.4, just after which there is a rapid rise in the hydrocarbon emissions and cycle-by-cycle variations in combustion. For the very weak mixtures (lambda above 1.5) flame propagation is slower, but more significantly the flame is more readily quenched. The increase in burn duration is not significant so long as ignition timing is optimised; a 10–90% MFB duration of 20° crank angle (ca) amounts to a 1%-point loss of efficiency, and even if this is doubled to 40°ca the loss of efficiency is only 3%-points. The valves do not operate instantaneously at the end of the stroke, and this means that the effective compression and expansion ratio will be around 11:1 with about a 2%-point loss of efficiency. At a lambda of 1.4 the Fuel-Air cycle would imply an efficiency of 0.53 compared with the experimental value of 0.43, so the biggest loss that has not been plotted in Fig 3.3 is of course heat transfer that will account for about a 7%-point loss of efficiency. Heat transfer has been reduced in diesel engines by thermal swing coatings [28, 29], but with SI engines if there is less cooling then there is an increased likelihood of combustion knock. However, auto-ignition can be exploited in Gasoline Compression Ignition (GCI) engines, as discussed in Section 5.2. It is also pertinent to compare dilution with air with dilution by EGR and some results from modelling are presented in Fig. 3.4, and like the data in Fig. 3.3 this is for a compression ratio of 13:1 and a fixed engine output. The data in Fig. 3.4 is from a phenomenological model [30] that has been constrained to operate adiabatically with instantaneous combustion so as to replicate fuel-air cycle modelling.

As expected, Fig. 3.4 shows that dilution by air increases the cycle efficiency, and the initial increase is rapid since the impact of dissociation is reduced, and for weaker mixtures the ratio of the heat capacities is increased. The increase in efficiency with EGR is perhaps unexpected in this context – it is unlike part load operation when the EGR will reduce the throttling loss. The efficiency has increased with EGR dilution because the lower cycle temperatures lead to lower levels of dissociation and there is small increase in the ratio of the heat capacities. The boost requirement for the fixed power density with dilution rises less rapidly than the dilution factor because of the rise in efficiency. These ideal cycle analyses have been for adiabatic compression and expansion, and it might be thought that the lower combustion temperature will reduce heat transfer. This is of course true, but to maintain a fixed power output the in-cylinder pressures will be higher so the heat transfer coefficients will increase; so the lower combustion temperatures will not necessarily improve the overall efficiency.

Evaporative cooling of the fuel during the induction in Gasoline Direct Injection (GDI) engines allows a higher compression ratio to be used (an increase of about 2 for a given quality fuel). GDI engines are also more amenable to boosting (supercharging or turbocharging) since fuel

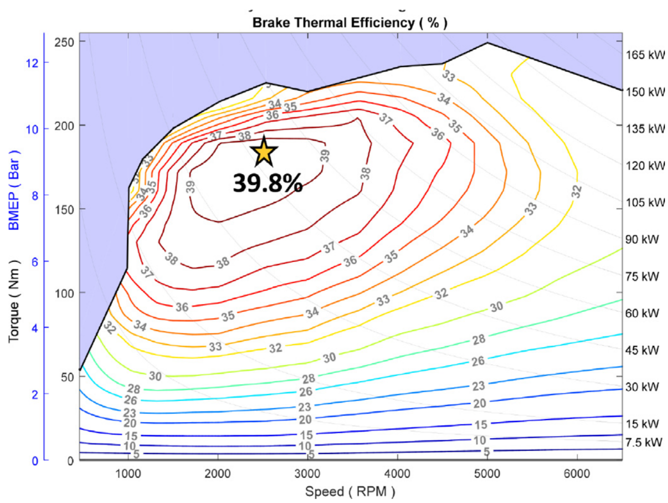

Fig. 3.5. Efficiency contours of Toyota 2.5 L Atkinson cycle engine when tested with an EPA Tier 2 fuel [32].

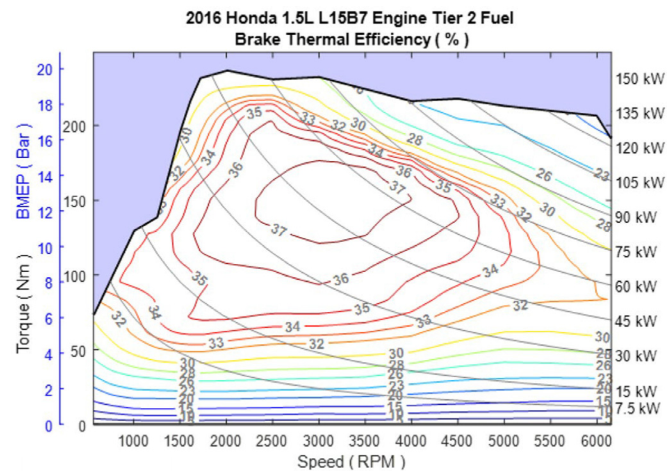

Fig. 3.6. Efficiency contours of Honda 1.5 L turbocharged engine when tested with an EPA Tier 2 fuel.

need only be injected after exhaust valve closure, so as to avoid short-circuiting losses. Boosted engines require a reduced compression ratio, but do enable the steady-state road load at cruising speeds to be at a part load condition that is un-throttled. Engine optimisation for vehicles cannot be separated from the transmission system, and this is discussed further in Section 3.4.

3.3. Performance of high efficiency, current market engines

3.3.1. Stoichiometric spark ignition engines

There are two current macrotrends in the development of conventional, high-efficiency SI engines – adoption of larger, naturally aspirated Atkinson or Miller cycle engines ($r_e > r_c$) and smaller, lower compression ratio downsized-boosted engines. As explained previously, the former seeks to enhance efficiency using valve timing to reduce pumping losses and knocking propensity while maintaining a large r_e, while the latter seeks to reduce pumping losses via turbocharging and to reduce the relative importance of friction and pumping losses by virtue of having a smaller engine that operates at higher loads.

An example of the Atkinson/Miller pathway is Toyota's spark ignition engine with a 40% brake thermal efficiency [31]; it is a naturally aspirated 2.5 L in-line four cylinder engine with a maximum power output of 150 kW that uses 91 RON fuel. It uses a long stroke to improve the volume to surface area ratio and a high turbulence intensity (allowing increased levels of EGR for a given level of combustion stability). As a long stroke increases the frictional loss (at a given engine speed) and reduces the volumetric efficiency there is a trade-off, and this engine has a bore of 1.18 times the stroke. The frictional losses are minimised by reducing the mass of the reciprocating components, using a variable displacement oil pump, a low viscosity oil (SAE 0W-16), and careful control of coolant temperature with an electrically driven pump. To optimise the part load fuel economy then an Atkinson cycle is used with a compression ratio reduced to 6.6:1 (from 13:1) to reduce the trapped volume without so much need for throttling.

A very comprehensive benchmarking of the engine [32], provides enormous detail on the engine operating regimes. The engine operates with stoichiometric mixtures for most of its envelope and the peak efficiency (40%) occurs with 23% cooled EGR and a brake mean effective pressure (bmep) of just over 9 bar at a speed of 2800 rpm; the mixture is only enriched for the highest speed and load conditions. Fig. 3.5 shows the efficiency contour map when the engine was independently tested with an EPA Tier 2 fuel (AKI of 87).

As well as reporting the brake efficiency there are contour plots of: inlet valve opening and closure, exhaust lambda, valve overlap, EGR level and ignition timing [32].

A good example of the downsized-boosted pathway is provided by Honda's recent 1.5L turbocharged direct-injection engine [33]. Like the Toyota engine, the Honda engine features a long-stroke design and various efficiency enhancing features such as sodium-filled exhaust valves (for knock mitigation) and dual cam phasing (for optimizing EGR and pumping losses).The corresponding brake efficiency contours, measured by the U.S. EPA, are shown in Fig. 3.6. Notice that at lower torque levels (below, say, 100 N-m) the efficiency of the Honda engine exceeds that of the Toyota – even though the peak efficiency of the Toyota engine is higher (this observation still holds true, though to a lesser extent, when the engines are scaled to provide the same peak power). At higher torque levels and low-to-moderate speeds, the Toyota has superior efficiency. Thus, we anticipate that the best engine with respect to fuel economy will be dependent on the relative frequency of high- and low-load driving, as well as the specific powertrain system the engine is paired with. Other factors will also impact the choice of engine technology, including low-speed torque, mass and size, and noise and vibration.

A logical further step toward improving engine efficiency would be to combine the naturally aspirated Atkinson/Miller pathway with the turbocharged pathway [34], as exemplified by the Audi TSFI and the VW EA211 engine series. These engines have demonstrated significant fuel economy benefits over the previous turbocharged versions – in the case of the TSFI the fuel consumption map was significantly improved over an earlier downsized boosted engine with a smaller displacement [35].

Although the engines described above are technology rich, there are additional technologies that can be applied to significantly enhance efficiency while maintaining stoichiometric operation – recent reviews can be found in [36-38]. One example, which has been deployed in numerous production engines since 1981 [39] and achieved a market penetration of approximately 20% of new light-duty trucks sold in the U.S., is cylinder deactivation. Deactivation has also been successfully applied to small three- and four-cylinder vehicles, including the VW engine mentioned above. By deactivating the valves of one or more cylinders at lower loads, it is possible to simultaneously reduce both engine friction as well as pumping and heat losses. In larger engines, the fuel consumption benefit can exceed 15% [40], while in the highly efficient engines discussed above the benefit is estimated to range between 2 and 3% [32, 41] Cylinder deactivation can also be used to help maintain catalyst temperature during periods of prolonged low load operation, making this technology particularly synergistic with lean combustion systems.

3.3.2. Lean and dilute SI engines

Section 3.2 demonstrated the desirability of operating with lean or dilute intake charge to achieve high efficiency. Current engine technologies all use EGR-dilution, as discussed above, to reduce pumping losses at lower loads and to mitigate knock at higher loads. Consequently, a great deal of engineering effort is expended to expand EGR tolerance though either improved in-cylinder flow motion [42, 43] or with advanced ignition systems [44-47]. The overwhelming advantage of EGR-diluted combustion systems is that they allow use of inexpensive, highly effective exhaust gas after-treatment – described in more detail below. Lean-burn engines, on the other hand, offer potentially higher efficiencies (*cf* Fig. 3.4), but require more expensive NO_x after-treatment. Under the current emissions regulations, this has limited their application to premium vehicles.

Recently, however, Mazda has introduced a lean-burn engine into the European market that does not require expensive NO_x after-treatment. The engine features a high compression ratio of 16.3, which enables very lean low-load combustion using a weakly stratified, spark-assisted compression-ignition combustion strategy. Here, a spark initiates a flame similar to a conventional SI engine, but the pressure and temperature rise in the unburned gases as combustion proceeds rapidly pushes the unburned gases into autoignition. At mid- to high-loads EGR is added to maintain low peak combustion temperatures, pressure rise rates, and NO_x emissions, while at the highest loads the engine runs as a stoichiometric SI engine – with knock control assisted by high levels of EGR, fuel injection during the compression stroke, and tailoring of in-cylinder fuel/air distribution and hence the end-gas mixture composition. By incorporating additional fuel economy enhancements due to careful thermal management, low viscosity oil, and friction reduction a vehicle equipped with this engine achieved approximately a 10% and 15% reduction in fuel consumption [48] over the New European Driving Cycle and Worldwide Harmonised Light Vehicle Test Procedure (WLTP), respectively, as compared to a comparable model equipped with a naturally aspirated Atkinson-cycle engine [49]. The U.S. EPA estimates [50] that a fuel consumption improvement of 12.5% is expected over the U.S. regulatory cycle when only efficiency gains associated with the lean combustion process are considered.

Cylinder deactivation is also applicable to lean combustion technologies and has several benefits [51] –including extending the stable operating range of lean homogeneous combustion and maintaining high exhaust gas temperature – a particularly important advantage for lean exhaust gas after-treatment.

3.3.3. Diesel engines

As discussed in Section 2.1, in diesel engines the fuel is injected near the top of the compression stroke and, for conventional high CN fuel, it autoignites nearly instantaneously. The compression ratio is not limited by knock, and high compression ratio coupled with lean operation and minimal pumping losses due to un-throttled operation results in very high efficiency. Limits to diesel engine efficiency are generally associated with trade-offs between efficiency and emissions – particularly NO_x. A comprehensive review of how engine design and operating parameters impact diesel engine efficiency can be found elsewhere [52, 53].

Despite their already high efficiency, new diesel engines continue to steadily improve. An example is found in the recent introduction of the Mercedes-Benz OM 654 engine family [54]. Combustion system improvement based on a 'stepped-lip' piston geometry [55] and higher peak cylinder pressure capability allows higher EGR rates to be used and combustion to be advanced, leading to higher efficiency while respecting the after-treatment system's NO_x reduction capabilities. Coupled with lower heat losses, and continued improvement in friction reduction, a reduction in fuel consumption of approximately 10% was achieved over the previous engine family, even while power was increased by nearly 15%. Based on this example, as well as demonstrated potential for brake thermal efficiencies as high as 46% using advanced combustion techniques [56], it is apparent that there is significant potential remaining to reduce the fuel consumption of the current diesel passenger car fleet, while meeting legislated emissions levels.

3.4. Powertrain performance

To best exploit the high-efficiency regions of the engine speed-load maps (Figs. 3.5 and 3.6), the engine must be paired with a transmission system with a wide ratio range. Shunt transmission systems (see Fig 3.7) can use an epicyclic gearbox to introduce a parallel transmission path, and this can incorporate a variable ratio drive.

As the shunt transmission is a linear system its overall speed ratio can be expressed as

$$\omega_o/\omega_i = R_e - R_v \tag{3.2}$$

The epicyclic gear ratio (R_e) is fixed but the variable ratio drive (R_v) can vary such that if the ratio is numerically equal there is a 'geared neutral'. This means that the engine can be rotating yet the wheels would not be rotating so there is potentially an infinite range of overall gearing ratios. The system can also be inverted so that the wheels are rotating but the engine is stationary. When R_v is greater than R_e then reverse is obtained. The variable ratio drive can be obtained mechanically with any Continuously Variable Transmission (CVT) or as in the Torotrak system which incorporates a shunt transmission system to give an Infinitely Variable Transmission (IVT) system [57]. The variable ratio drive can also be achieved electrically if a pair of electrical machines is used, such that some power is 'shunted' electrically. This concept dates back to the 1920s in the Thomas transmission system [58], and is well suited to hybridisation as the electrical machines can also be connected to a battery - as in the Prius [59]. Hybrid engine vehicles (whether series, parallel or shunt) enable the engine to be turned off when low power (say below 5 kW) is required.

The Toyota Prius, introduced in 1997, has a hybrid shunt transmission that is referred to as a Dual System, to distinguish it from the more familiar Series and Parallel systems [60].

Fig. 3.8 shows how a shunt transmission system (in this case the Toyota Prius Dual Hybrid) can lead to a low fuel consumption for a wide range of power outputs over the complete speed range. The engine had a maximum brake efficiency of 33%, so with automotive SI engines now achieving efficiencies of over 40% then a 250 g/kWh bsfc island should be achievable. For low power requirements the engine would be turned off and stored electrical energy would be used.

3.5. Modelling for high efficiency engines

It would be remiss not briefly to mention engine modelling. Advances in modelling capability have led to significant improvements in engine efficiency through an increased understanding of the processes undergone in an internal combustion engine. Modelling, of course, comprises a vast topic including 0-D, 1-D, and 3-D simulations (commonly known as computational fluid dynamics (CFD)). The models themselves (however many dimensions they are implemented in) are numerous and linked, but from a modelling perspective are essentially independent fields - combustion modelling, turbulence modelling, turbulence chemistry interactions, flow modelling and mixing, sprays (break-up–primary and secondary, droplet evaporation, droplet drag), and heat transfer to name but a few. A good overview can be seen in the recent book by Onorati and Montenegro [62], some useful review articles can be read in [63, 64], and examples of some applications in [65, 66].

4. Control of exhaust emissions

Exhaust emissions from vehicles broadly fall into three categories: local pollutant (gaseous), local pollutant (non-gaseous), and other pollutants. Each of these categories has their own control techniques, which can differ between engine types. The next two sub-sections will discuss

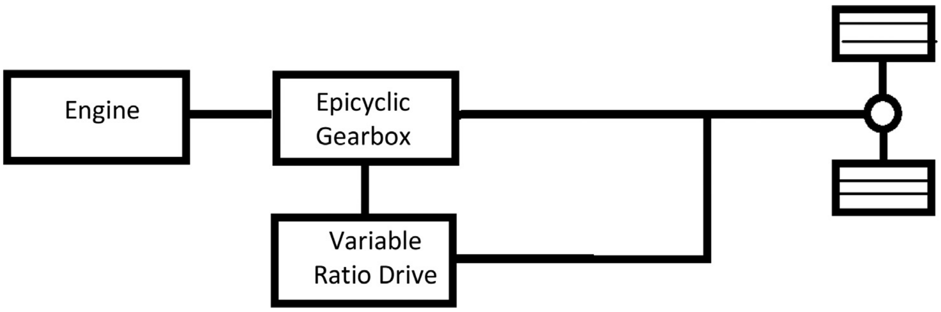

Fig. 3.7. Parallel power transmission paths in a shunt transmission.

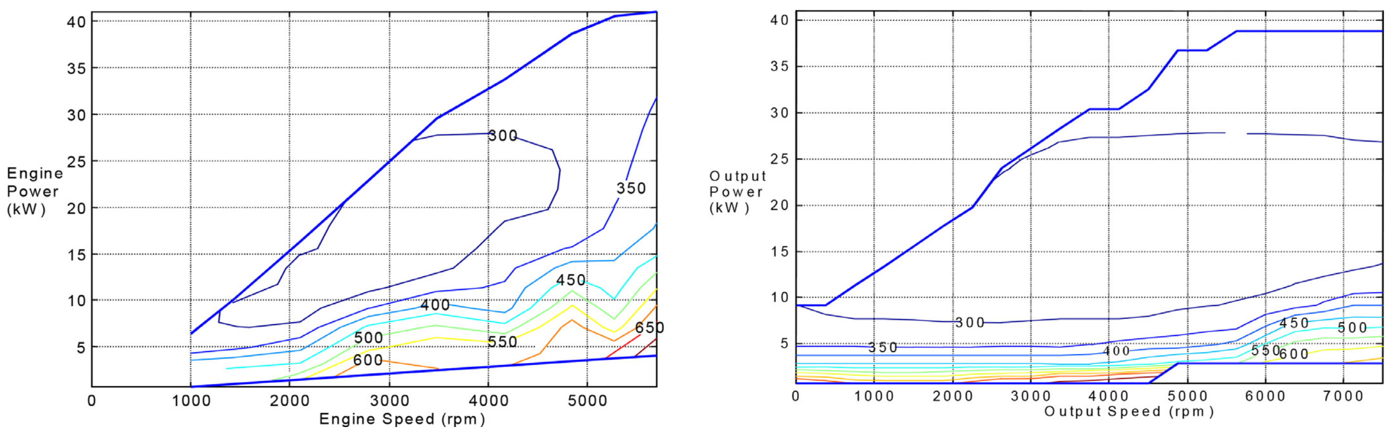

Fig. 3.8. Brake specific fuel consumption maps (g/kWh) of the Toyota Prius engine and the Dual Transmission System (allowing for electrical machine and power conversion losses [61].

Table 3
Summary of main emissions from vehicles and their typical control techniques.

Pollutant	Control (gasoline)	Control (diesel)
Unburned hydrocarbons (UHC)	Three-way catalyst (TWC)	Diesel oxidation catalyst (DOC)
Carbon Monoxide (CO)	TWC	DOC
Oxides of Nitrogen (NO_x)	TWC	SCR/LNT
Soot / Particulates	GPF / Uncontrolled	DPF
Carbon Dioxide (CO_2)	Uncontrolled	Uncontrolled
Water	Uncontrolled	Uncontrolled

the detail of the control of these emissions from gasoline and diesel engines, but a summary of the main emissions from engines is included in Table 3.

4.1. Gasoline emissions control

Gasoline engines have been fitted with catalysts for emissions control since the 1970s [19]. These were initially introduced to remove CO and UHCs from exhausts in response to smogs which were common in the USA then. In the 1980s the Three-Way Catalyst (TWC) was introduced to add control of NO_x.

4.1.1. Local pollutants (gaseous)

Today, the dominant control for all gaseous engine local pollutants is still the TWC. Rood et al. in their recent review of TWC technology [67] give a comprehensive overview of the state of the art. Gaseous local pollutant emissions from modern gasoline vehicles mostly occur in the first tens of seconds of engine operation, before the catalyst has reached its conversion temperature [68]. As a result, modern TWCs have significant storage capability for both NO_x and CO, enabling capture of these pollutants at cold-start and subsequent conversion once the catalyst has reached its optimum operating temperature [69]. TWCs require the engine to be operated with close to a stoichiometric AFR – this is to avoid the presence of oxygen in the exhaust. Lambda is therefore tightly controlled on today's SI engines, and removing this constraint provides a significant opportunity for the potential increases in efficiency required of gasoline engines. TWC development today focuses on the reduction in precious metal requirements (and hence cost) and reduced light-off temperatures and storage performance [67, 69]. One further area of development necessary is high temperature performance, currently enrichment is often necessary at high engine loads and speeds in order to limit the exhaust temperature and protect the catalyst; this has clear efficiency and particulate emissions penalties. TWC robustness to high-temperature will need to be improved in order to exploit these potential efficiency and emissions improvements [70]. Other pollutants can be emitted from gasoline (and diesel) engines that are not currently regulated such as ammonia (NH_3) (which is emitted today in higher levels from agriculture and is a significant source of secondary particulate formation) and nitrous oxide (N_2O) (an ozone depleter and extremely potent greenhouse gas). Currently levels of these are very low, but monitoring and research continues [71, 72].

4.1.2. Local pollutants (non-gaseous)

The main non-gaseous local pollutant from SI engines is particulate matter (PM). This consists of solid and liquid phase particles and arises predominately from inhomogeneities in the fuel-air mixture during combustion [73]. Liquid phase particles are typically unburned hydrocarbons, and can move between gaseous and liquid phases as conditions in the exhaust change. Solid phase particles are typically carbon, with adsorbed hydrocarbon species. A significant amount of research has been undertaken on PM formation and control measures, which shows, typically, that GDI engines have higher PM emissions compared to port fuel injection (PFI) engines [74]. Gasoline composition can also play a significant role in the level of PM emissions [75]. Engine out emissions control has proven surprisingly effective at PM reduction, increased injection pressures and injector design have consistently decreased PM emissions over the last decade [76]. For liquid phase particles, the TWC is an effective control technique – these particles being removed by the TWC as UHCs. For solid (and liquid) phase particles, the Gasoline Particulate Filter (GPF) has been shown to be highly effective in reducing PM emissions from gasoline vehicles, typical filtration efficiencies are in the range 60-99% depending on design and particle size [77]. Going forwards it is likely that high-efficiency GPFs will be fitted to gasoline vehicles, effectively removing PM emissions from them.

4.2. Diesel emissions control

Diesel engines typically produce higher levels of emissions on an engine-out basis than gasoline engines because of the unsteady diffusion flames inherent in diesel combustion. This unsteady, heterogeneous combustion process is typically (globally) lean and this lean combustion is one reason for diesel engines' higher efficiency than gasoline, however this excess of oxygen is also a challenge for diesel NO_x after-treatment systems. The heterogeneous combustion, while globally lean, has locally rich regions which lead to higher particulate matter formation (on an engine out basis) than gasoline engines. However, the excess of oxygen typically leads to very low levels of CO and UHC emissions.

4.2.1. Local pollutants (gaseous)

Similar to the TWC fitted to gasoline engines, the Diesel Oxidation Catalyst (DOC) has proven effective at removing UHC and CO from diesel exhaust. Further development of these catalysts today mirrors that of TWCs, with focuses on low temperature conversion and reduction in precious metal requirements [78]. NO_x removal from diesels has been an area of intense focus particularly because a TWC cannot typically be used on diesels as their lean operation means a TWC would not be effective in reducing NO_x. In common with all other pollutants, NO_x can be controlled using both engine methods (such as combustion system design, exhaust gas recirculation, or calibration) or after-treatment. On all modern vehicles the two approaches are used together. A modern after-treatment system would include a Lean NO_x Trap (LNT), which can store NO_x at low temperature, and a Selective Catalytic Reduction system (SCR) which can reduce NO_x at temperatures higher than ~200 °C. SCR systems are complex and expensive, requiring an aqueous urea solution (also known as AdBlue or Diesel Exhaust Fluid - DEF) injection upstream of the catalyst – and hence a separate tank and injection system for the DEF. An SCR is typically followed by an Ammonia Slip Catalyst (ASC) in order to remove any ammonia, required for the SCR reaction, from the engine exhaust. A comprehensive overview of NO_x reduction in after-treatment can be seen in Piumetti et al. [79], and Johnson et al. [80]. In common with all other catalyst technologies, current development includes reducing the precious metal requirements and reducing light-off temperatures. Additionally, for NO_x reduction, combinations of technologies including more than one SCR as well as an LNT are being considered in order to meet the most stringent legislative requirements.

4.2.2. Local pollutants (non-gaseous)

As with gasoline engines, the main local pollutants (non-gaseous) from diesel engines are PM. On an engine-out basis these are typically an order of magnitude or so higher than those from gasoline engines, however since the early part of this decade, almost all diesel engines have been fitted with a diesel particulate filter (DPF). These filters have very high (~99%) filtration efficiency, but need to be regenerated periodically, with an associated penalty on CO_2 emissions due to the high fuel consumption required to reach the high temperatures needed for regeneration. DPFs have also been combined with SCR as SCR on filter (SCRf) which is in common use. The use of a DPF creates a pressure drop in the exhaust, which does increase CO_2 emissions marginally for vehicles fitted with them. Future development of DPFs focusses on reducing this pressure drop as well as other improvements around filtration efficiency. These improvements notwithstanding, the introduction of the DPF has effectively removed particulate emissions from diesel vehicles.

As a result of this intense focus on diesel engine emissions, today's diesel engine after-treatment systems can be very complex; for example, one system to meet California's most recent proposed standards includes (in order from engine out to tailpipe) SCR-ASC-LNT-DOC-DPF-SCR-ASC [81] with both a close-coupled SCR for cold-start and a larger SCR system for warm operation. Such systems, while complex and expensive, can achieve near zero emissions at tailpipe for all diesel pollutants.

Table 4
NO_x emissions from ADAC RDE tests (2019) [83]

Car	RDE NO_x (mg/km)
Audi A8 50 TDI	15
BMW 520d Steptronic	5
BMW 520d Touring	1
BMW X2 xDrive 20d	23
Citroen Berlingo BlueHDI 130	7
Honda Civic 1.6 i-DTEC	101
Kia Ceed 1.6 CRDi	22
Mercedes A 180 d	40
Mercedes C 220 d	0
Opel Astra 1.6 D	1
Peugeot 308 SW BlueHDi 180	30
Volvo XC60 D5 AWD	56
VW Golf 1.6 TDI SCR	14

4.3. Real driving emissions

In Europe there has been a requirement since September 2017, and the introduction of the EU6dtemp legislation, for not only laboratory tests for exhaust emissions measurement, but also so-called Real Driving Emissions (RDE) testing. Such testing, introduced after the dieselgate scandal [82], uses portable emissions measuring systems (PEMS) attached to the tailpipe of a vehicle to measure its emissions on road under "real" conditions. Legislatively compliant test routes include an urban portion, a rural portion, and some highway driving. Such testing is intended to ensure that cycle-beating and illegal activities such as those performed in the dieselgate scandal are not possible.

In addition to legislative RDE testing, a substantial amount of independent RDE testing is being undertaken today as well. These tests do not drive the legislative RDE cycle, but use similar cycles also representative of "real" driving. ADAC (Allgemeiner Deutscher Automobil-Club) conducted tests of 13 new diesel vehicles in 2019; their results are shown in Table 4 [83]. All but one of the vehicles ADAC tested had very low levels of NO_x emissions in their testing, with five emitting less than 10 mg/km and the Mercedes C220d emitting 0 mg/km. At the time of writing, 382/829 vehicles tested by Emissions Analytics (an independent RDE tester) achieve their highest possible rating of A+ (indicating emissions lower than 0.06 g/km NO_x) over an RDE test [84]. Of these 382, 59 are diesel and 323 are gasoline, of which 22 are hybrids, and 10 are plug-in hybrids – all but one of the ADAC vehicles tested met this standard as well. This shows that today, all internal combustion engine technologies are capable of near-zero NO_x emissions, although clearly, not all are.

The presence of DOCs (only) on diesel vehicles up until the introduction of Euro 5 led to an increase in NO_2 monitored at roadside locations. Typically engine-out NO_x from a diesel engine has a low fraction of NO_2, unless very high levels of EGR are employed [85, 86], however the proportion of NO_2 of total NO_x emitted at tailpipe is increased by the presence of a DOC [87]. This is important because most Air Quality (AQ) monitoring only considers NO_2, and indeed NO_2 is considered to be more harmful to human health, and by the time NO has reacted into NO_2 in the atmosphere, it will have dissipated from the roadside. However, the effectiveness of SCR and other NO_x after-treatment technologies has led to real improvements in AQ measured at the roadside, with a recent paper noting *"The proportion of NO_x now being emitted directly from road transport as NO_2 is up to a factor of two smaller than the estimates used in policy projections."* [88] and "[*exhaust after-treatment has*] *led to substantial reductions in emissions of NO_2 in recent years from light duty diesel vehicles, which has contributed to reduced roadside NO_2 concentrations"* [89].

4.4. Long-term opportunities and trends

Given the capability of modern, well-designed after-treatment systems, which can allow vehicles to emit zero pollutants, where are the next opportunities and challenges for after-treatment? Going forward, durability is going to be a key requirement; EU5/6 specifies a vehicle life of 160,000 km. Globally, California LEV III specifies 240,000 km by 2025 and China 6b 240,000 km by 2023. In the heavy duty sector, CARB are in discussions to extend durability requirements to 1,000,000 miles [90]. Such requirements will clearly ensure further improvements in local air quality globally. These requirements, however, place significant demands on after-treatment systems, where thermal aging and ash build up can affect both conversion and filtration efficiencies of all filter and catalyst technologies. However, in parallel with these legislative drivers, the innovation of catalyst technologies continues, and there is every expectation that these durability requirements will be met [91].

Engine manufacturers are having to reconsider the balance of engine-out vs. after-treatment control techniques. If large and complex after-treatment systems are required to meet legislative requirements, then it can be cost effective to reduce any engine-out reduction technologies such as EGR or high fuel injection pressures and rely solely on the after-treatment system – particularly in heavy-duty applications.

There is often conflict between local pollutant removal and efficiency requirements. As engine efficiencies have increased, exhaust gas temperatures have been decreasing (as would be expected, lower heat rejection is a consequence of higher efficiency) [92]. Such a decrease in exhaust temperature reduces the energy available to heat the catalyst, and may delay catalyst light-off. Stop-start and other technologies have a similar effect. Similarly the pressure drops over complex after-treatment packages reduce engine efficiency. Future vehicles will require careful thermal management, as well as improvements in after-treatment to mitigate these.

Further efficiency improvements in gasoline engines may require a departure from stoichiometric operation [19]. As a result, gasoline after-treatment systems may begin to resemble diesel after-treatment systems, as it is likely that SCR would be required for NO_x conversion in lean gasoline operation [70].

The increasing hybridisation of vehicles and electrification brings new challenges. For example engines may not switch on for the first 10 or 20 miles of operation in a PHEV, and frequent stop-start events will mean that keeping temperature in catalysts (amongst other areas of a vehicle system) will be very important. Electrically heated catalysts may form part of the solution – potentially the catalyst could be warm before an engine even switches on (this may also remove the need for storage catalysts). Further integration with system thermal management – e.g., battery cooling and cabin HVAC may bring further synergistic benefits.

5. Scope for improvements in efficiency and emissions

5.1. Short to medium term opportunities

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 market place.

There are significant developments taking place to improve the efficiency of SI engines almost to the level of diesel engines [93-97]. In preparation for the discussion below, it will be useful to define the baseline vehicle to use as our point of comparison. A convenient choice is the U.S. 2017 passenger car new vehicle average in the U.S., which has both fuel economy, performance, and weight characteristic that are well documented [98]. This 'average' vehicle has a real-world fuel economy rating of 29.2 mpg (8.06 L/100 km). Considerable improvement over this baseline has already been clearly demonstrated – for instance, fuel consumption for the best-in-class passenger car in the U.S. market of similar size and performance is already 14% lower [99].

5.1.1. Engine technologies

In the short-term, efficiency improvements will be associated with the increased penetration of technologies that are already proven to be viable for commercialisation as these technologies become more broadly accepted and cost-effective. Cooled EGR, integrated exhaust manifolds, variable valve lift, variable geometry turbochargers, cylinder deactivation, and variable compression ratio are some example technologies among others. Neither the benefits nor the costs of adding multiple technologies are additive, and the many studies [36, 37, 100-102] which estimate both fuel efficiency gains and costs often conflate improvements due to advances in ICEs with improvements associated with aerodynamics, rolling resistance, vehicle mass, and the like.

Nevertheless, the potential fuel economy benefits from applying proven ICE technologies alone can be estimated with the U.S. EPA's Lumped Parameter Model [103]. Exercising this model against an "average" vehicle with a technology mix appropriate to a 29 mpg real-world fuel economy rating, we find that the current best-in-class vehicle in the U.S. market is predicted to lower fuel consumption by 13% – in reasonable agreement with the number cited above. Adding additional technologies specific to ICE powertrain improvement—turbocharged Atkinson, additional friction reduction, improved 12 V accessories, start/stop, continuously variable valve lift (which includes cylinder deactivation), and an 8-speed automatic transmission — the potential fuel consumption reduction rises to over 30%.

As a second point of calibration, vehicle-level improvements (better aerodynamics, rolling resistance, mass, etc.) can also be considered, achieving a total fuel consumption reduction of 43%. This compares favourably with estimates recently provided by Argonne National Laboratory [104] of up to 47% (when adjusted to our baseline vehicle).

Approaching the medium-term, additional technologies may be applied that have not been considered above. Although the Mazda SkyActivX discussed earlier is a successful introduction of a lean burn technology at a reasonable cost, advances in ignition systems may make lean combustion systems more accessible and cost-effective. By allowing mixtures sufficiently weak that the NO_x emissions are inherently low (lambda less than about 2), a pre-chamber combustion system can give a greater efficiency benefit than when diluting with EGR (see Fig. 3.4) while avoiding or minimizing expensive after-treatment. Pre-chamber systems have been developed on a number of occasions, and recent work in this area includes that of Mahle [105] and IAV [106]. The Mahle pre-chamber system and some brake efficiency data are shown in Fig. 5.1.

In the Mahle system some fuel is admitted to the main cylinder (by port fuel injection) but additional fuel is injected into the pre-chamber, and this is also where the spark plug is located. Upon ignition combusting gases leave the pre-chamber as a series of jets that can then ignite the very weak mixtures in the main chamber. The volume of the pre-chamber is about 1 cm^3, and the fast burn allows a high compression ratio (14:1) to be used. It can be seen in Fig. 3.6 that brake efficiency of over 40% is obtained over a wide operating range and that the bmep is high – this depends on having an effective turbocharger system.

Fuel does not have to be injected into the pre-chamber, and the performance of these "passive" pre-chamber ignition systems is discussed in great detail by Sens et al. [106] who show that the operating range is

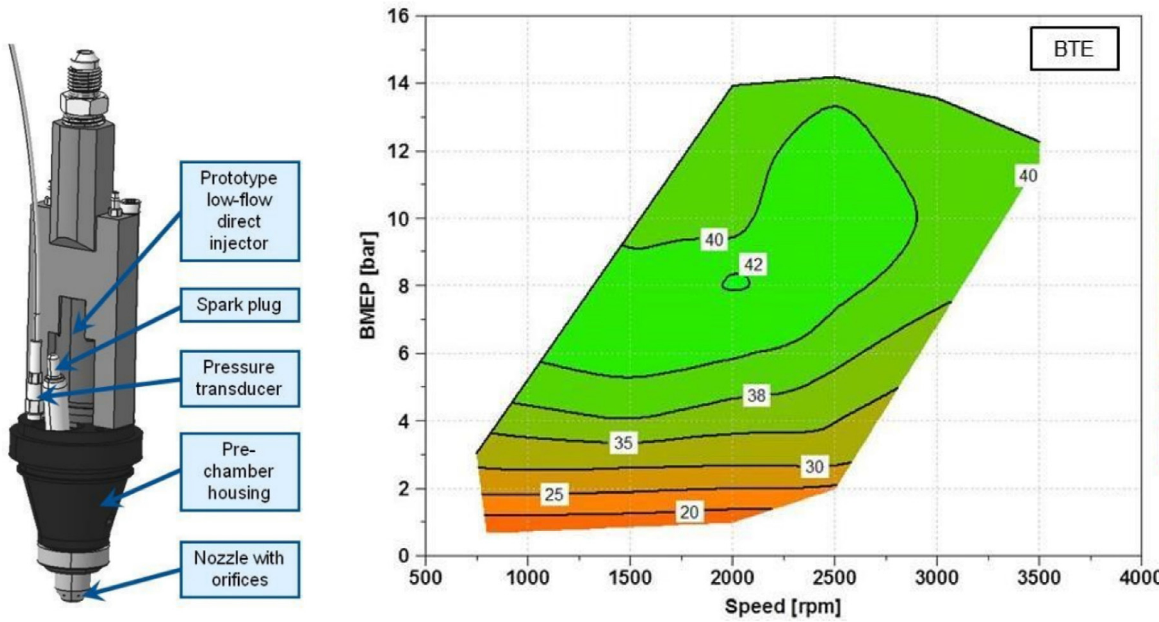

Fig. 5.1. The Mahle pre-chamber system and some brake efficiency data [106] (S10).

narrower than for an active pre-chamber system, but that its fuel economy can be comparable to an active pre-chamber.

Another technology that can provide significant improvements in the efficiency of conventional SI engines is water injection, either into the intake port or – more effectively – directly into the cylinder [37, 107]. Evaporative charge cooling associated with water injection can increase power density by increasing intake charge density as well as reduce knock – enabling a higher degree of downsizing, higher compression ratio, or more advanced combustion phasing. Each of these latter factors will also increase efficiency. It also lowers exhaust gas temperature, reducing the need for charge enrichment which likewise increases efficiency. When applied to a state-of-the-art boosted Atkinson cycle engine, water injection was able to provide an additional 1-5% fuel consumption improvement, depending on the drive cycle investigated [107]. An additional improvement of about 1%, also depending on the drive cycle, could be obtained if the compression ratio was increased to take advantage of the improved knock resistance.

Like water injection, variable compression ratio engines have yet to see significant penetration into the mainstream market, despite their potential for a sizeable reduction in fuel consumption. Variable compression ratio allows the fuel economy benefits at low-to-moderate loads of a high compression ratio engine, while maintaining the high power-density benefits of a lower compression ratio, turbocharged engine. Fuel economy improvements compared with a downsized, turbocharged engine are estimated to be approximately 5%, and are expected to be largely retained when applied to a boosted Atkinson/Miller engine [37].

5.1.2. After-treatment technologies

Similarly, after-treatment systems have also developed and continue to develop to reduce exhaust pollutants such as particulates, NO_x, CO and HC [108-110]. For instance, modern diesel particulate filters (DPFs) and gasoline particulate filters almost entirely eliminate particulates from ICE exhausts [108, 110]. Indeed, in some circumstances, a DPF may make the particulate emissions in the exhaust so low, that they are lower than the atmospheric ambient – i.e., the ICE is actually cleaning the air [111]. 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 [108]. Even NO_x levels in diesels can be reduced to levels much lower than European limits set for 2020 with a modern exhaust catalyst and intelligent management of combustion temperatures and modes [109, 112].

5.1.3. Fuel implications in the short term

Engine combustion system developments also have implications for fuels. For instance, 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. As pressures in the cylinder increase, preignition which can lead to extremely high intensity knock, known as superknock, becomes more likely [104] and will limit the scope for turbocharging and downsizing. High anti-knock quality of fuels will help to avoid knock and mitigate superknock [104] and will enable higher efficiency SI engines. Pressure to increase the anti-knock quality of gasolines to enable high efficiency SI engines will grow. For instance, there are suggestions [113] that by 2040 all gasoline in the U.S. should have RON > 98 whereas currently U.S. regular, the most commonly used gasoline, has a RON of around 92. Whether such a change will bring about benefits in GHG needs to be assessed on a life cycle basis and the answer might be different for different refinery configurations. This will require big changes and investments in refineries and will further increase the availability of low-octane gasoline components such as naphtha [114, 115] because the opportunity to blend them in gasoline will decrease. The importance of high-octane components like ethanol, MTBE, di-isobutylene and methanol will also increase.

An important question is how fuel anti-knock quality should be defined in such modern engines [20, 22, 116] because this has major implications for fuels manufacture which is geared towards meeting fuel anti-knock specifications. Currently gasoline anti-knock quality is defined by RON and MON. They are measured by comparing the gasoline with blends of iso-octane and n-heptane, known as primary reference fuels (PRF) in the single-cylinder CFR (Cooperative Fuels Research) engine according to test procedures set by ASTM (American Society for Testing and Materials). For practical fuels, RON is higher than MON and the difference is known as sensitivity, S. The pressure for a given unburned mixture temperature is lower in the MON test compared to the RON test. Practical gasolines contain aromatics, olefins and oxygenates which respond very differently in chemical kinetic terms to increasing pressure compared to PRF which are used to define the RON and MON scales. Practical fuels are much more prone to autoignition and knock under the MON test conditions compared to PRF. However, SI engines have been moving away from the MON test condition 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 [21, 117]. In fact, in modern engines a lower MON fuel, for a given RON, i.e., a fuel that has higher sensitivity for a fixed RON, has better anti-knock quality [20, 22, 116]. However, in many areas e.g., U.S.A. and Europe, MON is considered to contribute to anti-knock quality, i.e., high MON is considered desirable. As engine designers seek to further improve engine efficiency, this mismatch between specifications and engine requirements will get wider and will have to be addressed. One approach might be to replace the octane scale with a different one based on toluene/n-heptane mixtures (toluene reference fuels, TRF) rather than PRF. The fuel would be tested in the RON test and assigned a toluene number, TN, the volume percent of toluene in the TRF that matches it for knock [118]. At the very least countries which specify gasoline anti-knock quality by RON alone, like Japan, should not introduce a minimum MON specification.

In addition to knock, conventional fuel-related concerns such as ignition, flame development, deposit formation and control [23] and pollutant formation will continue to be of importance as SI engines seek ever higher efficiency. There is persistent pressure to reduce sulfur levels in both gasoline and diesel to enable effective after-treatment systems. Fuel additives [23, 119] are routinely used to control deposits in the fuel system.

Alternatives to conventional petroleum-based liquid fuels such as biofuels; hydrogen; natural gas – both as compressed natural gas (CNG) and liquid natural gas (LNG); synthetic fuels; methanol; liquid petroleum gas (LPG); ammonia; dimethyl ether (DME) and electrofuels are being actively developed [12]. Often, energy security or the desire to reduce petroleum imports rather than the control of GHG is the main driver for such developments. Of all these alternatives it is the biofuels, primarily as ethanol, that are very well established, accounting for about 2.5% of global transport energy demand. However, all these alternative fuels start from a very low base and, though their use will grow, face significant barriers to unlimited and quick growth as transport fuels [12]. Most credible projections [9,10] suggest that alternative fuels would not account for more than 10-15% of global transport energy by 2040; this is still a very large change since 10% of transport energy represents over 1.1 billion litres of conventional liquid fuels every day. At the same time, the use of such alternatives makes sense somewhere/sometime and hence their use will grow.

5.2. Medium to long-term opportunities

Medium- to long-term approaches to improved engine efficiency that are being developed include compression ignition approaches that use market gasolines [95, 96], although there is scope to develop affordable and highly efficient new fuel/engine systems to meet the increasingly stringent requirements on GHG emissions and local air quality if engines are not confined to using current market fuels. Such systems would be able to leverage GHG benefits from fuel manufacture by using fuels primarily made up of low-octane gasoline components that are less processed and hence have a lower carbon footprint. Such fuels are also likely to be in surplus and hence could be cheaper than conventional diesel or high-octane gasoline. Of course, this 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.

5.2.1. Gasoline compression ignition (GCI)

The gasoline direct injection compression ignition engine is similar to the Mazda system discussed above in that it can use market fuel, but it does not rely on spark ignition and partial combustion via flame propagation to achieve autoignition and to control combustion timing. Premixed compression ignition has demonstrated diesel-like efficiency [96] using U.S. market gasoline, but has additional advantages associated with its lower engine-out emissions. Soot formation can be eliminated in CI engines if the fuel and air are sufficiently premixed before combustion; then exhaust gas recirculation (EGR) can be used to reduce temperature and oxygen content to minimize NO_x [120]. Modern diesel engines use high-pressure injection systems to promote premixed combustion, but even then have to use sophisticated after-treatment systems to bring down exhaust soot and NO_x to acceptable levels, making them very expensive. GCI engines are simply diesel engines running on gasoline-like fuels. The high ignition delay of such fuels allows much more time for the fuel to mix with air in the cylinder and makes it much easier to control soot and NO_x. Moreover, the RON of the fuel can be much lower than that of current gasolines.

The advantages of the GCI concept are –

(a) The engine will be at least as efficient and clean as current diesel engines but will be less complicated and hence cheaper (lower injection pressure, simpler after-treatment because the focus shifts to controlling CO and HC rather than soot and NO_x).
(b) The optimum fuel will be less processed and hence easier to make compared to current gasoline or diesel fuels.
(c) It provides a path to mitigate the global demand imbalance between heavier and lighter fuels that is otherwise projected. The alternative is investment in refineries to make the required diesel and jet fuel while the diesel engine continues to be expensive in order to meet increasingly stringent NO_x/soot requirements.
(d) It reduces investment requirements by refineries and ensures more efficient refinery operation by providing a home for “homeless hydrocarbons” [114, 115].

The concept has been well-demonstrated in research engines but development work is needed to make it feasible on practical vehicles, e.g., on cold start. Significant progress has been made in this regard to develop the GCI concept using U.S. regular gasoline. In addition to the high efficiencies described below, well-to-wheel analyses show that when combined with a 70 RON fuel, the GHG footprint of a GCI engine will be lowered by approximately an additional 5% – associated with the lower energy demands for fuel manufacture [121, 122]. When GCI is compared to an equivalent diesel engine, the GHG impact of such a GCI engine would be around 5% lower with the benefit coming primarily from fuel manufacture.

The most advanced demonstration of a GCI engine is associated with Sellnau and co-workers, [96, 123, 124] who have developed and tested a prototype multi-cylinder engine. The engine features a compression ratio near 17, fast intake air heaters to aid in cold-start and combustion phasing control, a stroke-to-bore ratio near 1.3, a 500 bar capable fuel injection system, and a 2-step exhaust cam to enable exhaust re-breathing for low-load operation. At loads above 5 bar, the engine uses a double injection strategy whereby the second injection controls combustion phasing and pressure rise rate, but burns in a largely non-premixed mode. Accordingly, NO_x and soot emissions are expected to be considerably higher than for conventional SI combustion systems. When operated without EGR, the engine provides a peak brake efficiency of 43.2%, with a broad range of speeds and loads above 40% (see Fig. 5.2). The light load performance is also extremely good. At 1500 rpm and a load of about 2 bar BMEP (a highway moderate speed cruise condition), the BSFC is between 245–250 g/kW-h, corresponding to a thermal efficiency approaching 34% – a number that compares favourably with modern diesel engines. With EGR the benefit will be a few percent lower, but as shown in Fig. 5.3 the modelled fuel consumption on the US combined regulatory test is reduced by over 25% compared to their baseline vehicle (23% compared to our baseline vehicle). Placing this in perspective using the Lumped Parameter Model, this is an improvement of ~5% over a stoichiometric SI engine incorporating a comparable level of technology. With potential further advances mainly associated with heat loss reduction (Gen4X), and by coupling to

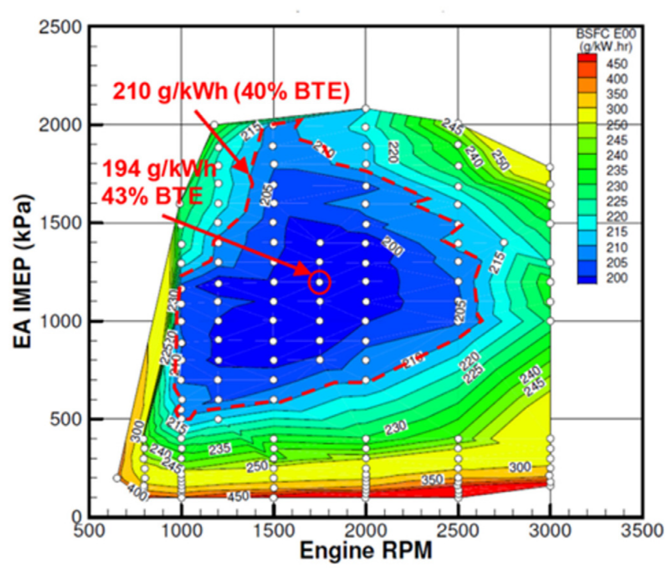

Fig. 5.2. BSFC/BTE map for the Delphi Generation 3X GCI engine. From [123].

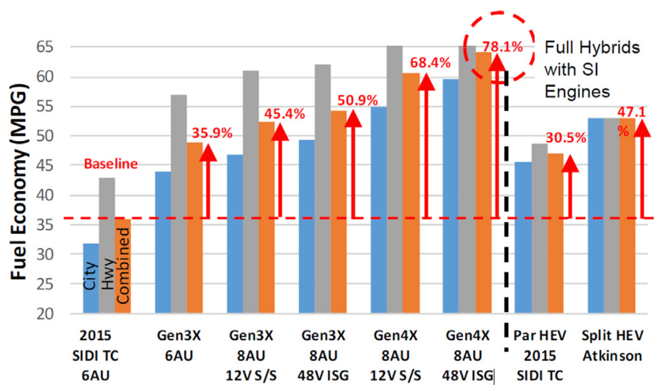

Fig. 5.3. Modelled fuel economy gains over the U.S. regulatory test cycle. From [123].

48 V mild hybridisation, an estimated reduction in fuel consumption of nearly 45% is obtained.

An alternative strategy for operating a GCI engine is to premix the fuel and air completely before combustion occurs as in a HCCI engine. However, this creates challenges with meeting the required speed and load range since the requirement for fuel autoignition quality or ignition delay (ID) in CI engines varies with pressure and temperature in the engine. For instance, high ID in the fuel would be desirable at high loads when soot formation is a problem while at low loads when autoignition is difficult, a low ID will be beneficial. One way to meet these challenges, and to enable rapid combustion phasing control, is to adopt an injector concept that allows tailoring of fuel reactivity by metering in small quantities of an ignition enhancing additive. With this strategy, power densities exceeding conventional diesels (> 18 bar bmep) can be achieved while respecting noise constraints [125] and the emissions problems associated with non-premixed combustion are avoided, such that it may be possible to operate without a particulate filter and with minimal NO_x after-treatment. A map of brake thermal efficiency measured using this strategy is shown in Fig. 5.4. In comparison with Fig. 5.2, we see both higher peak thermal efficiency and a broader area where brake thermal efficiency exceeds 40%. In the important regulatory cycle area between 1000 and 2000 rpm and 20–150 N-m of torque, the premixed strategy should deliver an additional 5–6% reduction in fuel consumption over the Gen3X Delphi engine. With additional measures taken to increase efficiency such as were applied to the Gen4X and

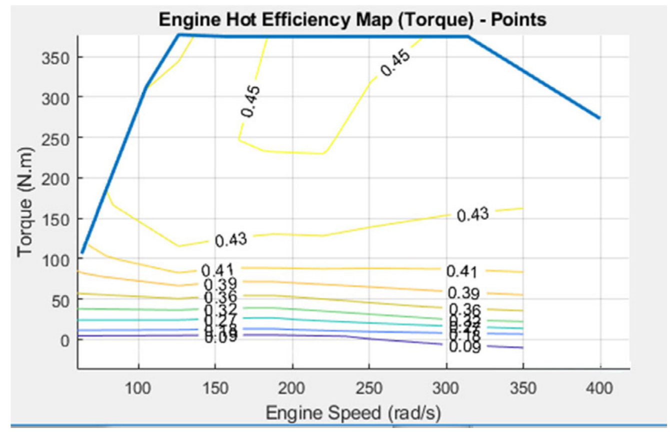

Fig. 5.4. Brake thermal efficiency measured for a premixed GCI concept [126]. The torque axis was developed assuming a displacement of 3.5 L, such that the peak torque curve shown underestimates the demonstrated potential of this concept.

mild hybridisation, we expect the fuel economy to rise to approximately 68 mpg, and 75 mpg is within reach with full hybridisation. This represents a 50% reduction in fuel consumption compared with our baseline, the 2017 U.S new car average.

5.2.2. Reactivity controlled compression ignition (RCCI)

Reactivity Controlled CI (RCCI) is another way to meet the requirement of varying ID at different operating conditions [127-131]. In the RCCI concept, a fuel with high ID such as a market gasoline or ethanol [127, 128] or natural gas [129] is injected in the port and ignition is triggered by the direct injection of a fuel such as commercially available diesel fuel, with low ID, near top dead centre. Depending on the engine operating condition, the ratio of the two fuels used is changed e.g., relatively more diesel fuel is used when autoignition is difficult as at low loads. However, the amount of diesel fuel used is around 10% of the total fuel used over a normal operating cycle. In an approach similar to the second GCI strategy described above, 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 inject this reactive fuel, rather than diesel fuel, to trigger ignition [130]. RCCI combustion can have 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 [131]. 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 misfuelling could also be reduced in fleet operations with centralized fuel provision. Hence RCCI is probably better suited for commercial fleet operations. Widespread adoption of RCCI in heavy-duty engines should help moderate the expected increase in demand for diesel fuel.

5.2.3. Octane on demand (OOD)

Many of the technologies discussed above for increasing SI engine efficiency in the short-term were aimed at improving the knock resistance of the engine. However, high octane is usually needed in SI engines only in a small fraction of the engine's operating region [132-137]. Octane on demand (OOD) makes the best use of available fuel octane quality. The engine carries a high and low-octane fuel and will have two fuel injection systems. These components can come from separation of the single gasoline currently available at the pump [132, 133] or separately sourced and stored on the vehicle [134]. Such an approach allows the engine to be redesigned (e.g., higher compression ratio) to improve efficiency [132, 133]. Alternatively, with the same compression ratio, the engine can use the high-octane fuel only a part of the time when it is needed and 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 GHG on a well-to-wheel basis even if the engine compression ratio is not increased [122, 137]. Both GCI and RCCI engines would also benefit from an OOD system, as the low octane fuel would assist with low load autoignition while the high-octane fuel can extend the range of high-load operation.

5.2.4. Opposed piston engines

Opposed piston engines are older than the automotive industry, having 2 pistons in each cylinder with 1 or 2 crankshafts for each cylinder [138] and 3 cylinders with 3 crankshafts [139]. When 2 crankshafts per cylinder are used there is scope for controlling the phasing to increase the period for near constant volume combustion. Recent work with 2-stroke opposed piston diesel engines uses uniflow scavenging – one piston controls the inlet ports and the other piston controls the exhaust ports. With no cylinder head there is less heat transfer and this leads to a higher efficiency. A brake efficiency of 55% is predicted for a 9.8 L 3 cylinder diesel engine based on a validated model of a 4.9 L 3 cylinder opposed piston engine [140]; the power output is predicted to be 342 kW at 1800 rpm. A proposal for a light duty engine with a 0.9 L displacement has an output of 80 kW at 4000 rpm and this is comparable to a 1.2 L conventional engine. The opposed piston engine will be operating with weaker mixtures, and this too contributes to the higher efficiency of the opposed piston engine [141]. Work is also being progressed on a 4-stroke opposed piston gasoline engine [142] that uses a sleeve valve to control the gas exchange processes. Unlike a conventional sleeve valve engine the junk rings and heads will not be needed. Mixture preparation with gasoline will be easier than with diesel fuelling, so there are attractions in using a 2-stroke opposed piston engine for gasoline compression ignition (GCI) operation, and comparable efficiency to operation with diesel has been achieved [143].

5.3. Long-term opportunities

As electricity generation decarbonises further, this renewable electricity could be used to manufacture batteries and run BEVs, taking their GHG footprint towards zero on a life cycle basis. However, as fuel consumption of ICEs also decreases, as discussed in this paper, the GHG impact of ICEs will also decrease proportionately and reduce any advantages BEVs running on renewable electricity might have in terms of GHG emissions. In fact, the availability of sufficient renewable or carbon-free electricity is a prerequisite for other alternatives as well if reduction of GHG is the primary aim. However, this is a long-term option given the very large demand for transport energy.

For instance, there is much interest in electrofuels or e-fuels which can be hydrocarbons – liquid or otherwise - made with CO_2 and hydrogen or hydrogen itself. E-fuels will have a very low GHG footprint if they are made using renewable or nuclear energy. Hydrogen could be made from the electrolysis of water and could 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. 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 [12, 144]. However, even replacing only aviation fuel with e-fuels is extremely challenging. In one study, the efficiency of conversion of renewable electricity to e-fuels is estimated to be 44% [144]. The current daily global demand for aviation fuel is 0.049 exajoules, in energy terms – Table 2. So the global need for renewable electricity to make sufficient e-fuel to replace the current demand for aviation is 0.1114 exajoules or 31 TWh daily. This means the world will need 1295 GW of continuous carbon-free power generation through each day to meet the demand for aviation fuels. This is equivalent to building over 430 nuclear power stations of 3 GW capacity, the size of the Hinkley Point C power station in the U.K. or around 1.1 million wind turbines of 3 MW capacity (assuming a capacity factor of 0.4). It is very unlikely that globally, there is sufficient economic or technical capacity to undertake such a vast expansion of carbon-free electricity in the short to medium term. However, 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 fuels. Indeed, approaches such as e-fuels should be seen as ways to enable easier expansion of renewable electricity generation rather than a solution to decarbonise transport in the short to medium term.

6. Conclusion

Currently around 99.8% of transport is powered by combustion engines and around 95% of transport energy is provided by petroleum-based liquid fuels; every alternative starts from a low base and faces very significant barriers to unlimited expansion. Hence, even by 2040, 85–90% of transport energy is expected to be provided by conventional fuels powering combustion engines. It is imperative that the performance of such engines is improved in terms of efficiency and exhaust pollutants if current greenhouse gas emission targets are to be achieved. There is a lot of scope for such improvements as discussed in this paper.

In the short-term, implementing technologies that have been proven commercially viable in conventional, stoichiometric SI engines can lead to an estimated 30% reduction in fuel consumption over a current typical new car. Additional technologies not considered in reaching this estimate, including lean-burn SI combustion, water injection, and variable compression ratio are expected to reduce fuel consumption further. In the medium term, lean-burn technologies incorporating some degree of compression ignition are expected to result in a further improvement of ∼10%, such that a fuel consumption reduction associated with IC engine improvements alone approaching 40% is feasible for engines used in light duty vehicles, which currently are predominantly SI engines. With hybridisation the high efficiency region is greatly extended (Fig. 3.8) and with the high efficiency engine concepts that have been described here, SI engines may never need to operate with a brake efficiency below 40%. The relatively small expected additional benefit associated with lean-burn technologies is initially surprising, but it must be recalled that the point of comparison is a highly optimized SI engine with low pumping losses and a high compression ratio. One of the key advantages of lean-burn compression ignition technologies is their ability to deliver high efficiency without necessarily requiring a high-octane fuel, potentially providing additional greenhouse gas savings associated with fuel manufacture as well as helping to balance demand for refinery output streams in terms of their efficiency and design.

New diesel engines show significant (up to 10%) fuel consumption improvement over previous versions, which are already very efficient. However, they suffer from high levels of PM and NO_x in the exhaust and require sophisticated and expensive after-treatment. However, current after-treatment technologies can deliver extremely low levels of NO_x and PM in real-world use – well below the levels required by legislation. In the medium term, there is scope to make it easier to control these pollutants using gasoline-like fuels rather than diesel, via GCI and RCCI approaches. If a low octane gasoline is used, there is further scope for reducing their GHG footprint through GHG savings in fuels manufacture. Particulate filters are very commonly used in modern diesel engines and are likely to be required even for SI engines. Exhaust particulates are virtually eliminated when particulate filters are used and other sources of PM such as from tyre and brake wear become important. If regenerative braking is used as in hybrid electric vehicles, brake wear does not exist. The levels of PM from tyre wear will be higher for a BEV because of the higher weight of the vehicle resulting from the weight of the battery, when compared to an equivalent HEV using a SI engine. In any case, after-treatment technology has developed to ensure extremely clean exhausts both for SI and diesel engines.

In summary, the fuel consumption and hence the GHG impact of SI engines can be significantly reduced using existing technology – the best in class fuel consumption is already around 14% lower compared to the average. Fuel consumption can be reduced by 30% through engine development alone and with new approaches using compression ignition such as GCI, may exceed diesel-like efficiencies. Using other technologies like hybridisation and light-weighting, fuel consumption could be reduced by 50% compared to the current average for light-duty SI engine vehicles. For both SI and CI engines, exhaust pollutants can be controlled to levels well below the requirements of current legislation.

Although some countries have ambitions to remove IC engine vehicles (ICEVs), this will take time even in the light-duty sector, as there will be a need for:

- increased electrical power generation capacity (and possibly storage too),
- changes to the electricity distribution system and
- the development of smart charging systems and other infrastructure requirements that will be different in different countries.

It is particularly difficult, if not impossible, to run heavy duty road, marine and air transport, which account for more than 50% of global transport energy demand, entirely on electricity because of the very large size and weight of batteries that will be needed. While this change is happening research and development in IC engines should continue because, as this paper has demonstrated, there is still scope for significant improvements in reducing fuel consumption and emissions. Moreover, IC engines burning renewable e-fuels can ease the expansion of renewable electricity generation by providing an alternate storage option when generation exceeds demand. Banning the sale of new ICEVs, as some countries propose to do, will stop needed research and development well before the deadline for such a ban as manufacturers dismantle their ICEV operations and will limit options available to renewable electricity suppliers. All available technologies should be developed and used to mitigate the environmental impacts of transport.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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