Energy Policy 36 (2008) 4657–4667

Contents lists available at ScienceDirect

Energy Policy

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

Science review of internal combustion engines[☆]

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ARTICLE INFO

Keywords:
HCCI
Hybrid engines
Rankine engine

ABSTRACT

Internal combustion engines used in transportation produce about 23% of the UK's carbon dioxide emission, up from 14% in 1980. The current science described in this paper suggests that there could be 6–15% improvements in internal combustion fuel efficiency in the coming decade, although filters to meet emission legislation reduce these gains. Using these engines as hybrids with electric motors produces a reduction in energy requirements in the order of 21–28%. Developments beyond the next decade are likely to be dominated by four topics: emission legislation and emission control, new fuels, improved combustion and a range of advanced concepts for energy saving. Emission control is important because current methods for limiting nitrogen oxides and particulate emissions imply extra energy consumption. Of the new fuels, non-conventional fossil-derived fuels are associated with larger greenhouse gas emissions than conventional petroleum-based fuels, while a vehicle propelled by fuel cells consuming non-renewable hydrogen does not necessarily offer an improvement in emissions over the best hybrid internal combustion engines. Improved combustion may be developed for both gasoline and diesel fuels and promises better efficiency as well as lower noxious emissions without the need for filtering. Finally, four advanced concepts are considered: new thermodynamic cycles, a Rankine bottoming cycle, electric turbo-compounding and the use of thermoelectric devices. The latter three all have the common theme of trying to extract energy from waste heat, which represents about 30% of the energy input to an internal combustion engine.

0. Introduction

As part of a project on energy, the Government Office for Science requested a science review of internal combustion engines[1] (ICEs), to be arranged in two main sections: (i) the state of current science and (ii) future advances to 2050 and beyond. This paper reports on key challenges and key scientific advances and on the likelihood of occurrence, capability and application of these advances. The paper, with one brief exception, limits consideration of these topics to the tank-to-wheel energy[2] consumed by ICEs as applied to road transportation.[3] Modifications to the prime mover, such as its hybridisation, are within the scope of the paper but those downstream of the gearbox[4] are not. The paper makes no comment on the commercial viability of the technologies.

The paper is based, wherever possible, on quantified statements of energy consumption which are, for current engine designs, accurate to about 2 percentage points (that is to say: statements about relative economies of the various current technologies of the form '*x*% more economical' should be read as '$x\pm2\%$ more economical of energy'). The uncertainty increases with the year of prognostication (and is quantified in tabular form later): there is little rational argument available to assess the magnitude of the uncertainty by 2050. Therefore, given the (stated) uncertainties as well as the financial and energy costs associated with the production and distribution of fuels and with 'combined' technologies, the figures relating to the state of affairs beyond '2010+', presented in this paper, should be used with

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[☆] While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

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[1] Overwhelmingly, four-stroke cycle, reciprocating piston engines. (This paper contains footnotes for completeness but the main text can be understood without reference to these.)

[2] A comprehensive discussion of the well-to-tank energy (i.e. the process from winning the primary energy source, usually crude oil or natural gas, manufacturing the fuel, in a refinery, and distributing it to the ICE) is beyond the scope of a paper of this length.

[3] Hence the energy is considered, implicitly or explicitly, in terms of the consumption in, say, Joules/km of a suitable reference automobile and over a relevant drive cycle (rather than the more restrictive consideration of energy in terms of 'specific fuel consumption' or thermal efficiency). This paper concentrates on this application of ICEs because it dwarfs the energy consumed by ICEs in other applications such as marine transportation and stationary power generation.

[4] For example, weight reduction of the vehicle, improvements to the rolling resistance coefficients including tyres, extensive considerations to developments in auxiliary electrical load, improvements to gearbox design and improved aerodynamic drag are outside the scope of this paper.

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doi:10.1016/j.enpol.2008.09.001

considerable caution when planning research and development investment. Indeed, if this was not the case, given the very considerable investment by all major motor companies, a consensus on the optimum technological solution would have emerged by now—whereas the companies are clearly hedging their bets by developing various solutions in parallel.

The key challenges for ICEs in the context of energy are, in arbitrary order:

(a) to reduce the effect of ICEs on climate change due to emissions (of greenhouse gases,[5] mainly CO_2 but also N_2O, and of particulates).
(b) to use in ICEs new fuels, developed in the context of either sustainability or energy security (e.g. gas to liquid, bio-derived), consistent with challenges (a), (c) and (d).
(c) to reduce the effect of ICEs on health due to their emitting noxious pollutants (e.g. NO_x, particulates, aldehydes, etc.). This challenge is related to energy because many[6] of the measures to reduce, or limit, the emissions of noxious pollutants are costly in terms of energy. It is an important challenge because the legislation[7] associated with emissions has arguably been the key challenge in the past two decades, and so inevitably determines the current scientific challenges and is certain to remain a key driver for at least the next decade.
(d) to reduce[8] the consumption of primary energy resources, particularly in the context of 'security of supply'.

1. Current science in ICEs: 2010+

1.1. Evolved baselines

The lead time, and the cost of development, associated with meeting existing and imminent legislation for ICEs is such that 'current science' determines to a large extent the technology level in ICEs about a decade hence. The 'evolved baseline' (Weiss et al., 2000) refers to the evolutionary development using traditional technologies.[9] Within Europe, the baseline is made up of engine types as follows: the port injection spark ignition engine (PISI), the direct injection spark ignition engine (DISI), and the direct injection compression ignition engine (DICI). Each is expected to evolve over the next decade, although each has different current energy requirements and different potential for evolution over the next decade, as will become clear below. Table 1 provides a detailed overview of the science presented in the sub-sections that follow according to the engine type and according to the application area of the science.

1.2. Key challenges

To illustrate the challenges, Table 2 shows a recent estimate (Edwards et al., 2006a–c) of the change in the energy consumption of a typical mid-sized passenger car[10] for a given set of performance criteria[11] over approximately a decade (2002–2010) leading to the year '2010+' ('…[an] assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2010 and beyond…'). The key challenges for the 2010 evolution are to deliver (acronyms are explained in Table 2):

- fuel efficiency improvements[12] for the gasoline- and compressed natural gas (CNG)-fuelled PISI and DISI, which will be

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[5] The CO_2 emission (for example, in g CO_2 eq/km. The relationship between the energy consumed and this emission depends on the fuel that is burnt) is of importance because this molecule is a potent 'greenhouse gas' that can contribute to climate change. The fact that 'well-to-wheel' emissions depend strongly on the source of fuel—particularly biofuels and hydrogen—is not discussed at any length in this paper. However, it is worth noting that in the UK, emissions from this application currently constitute about 23% (Brailsford and Salathiel, 2006) of the total CO_2 emissions (which, incidentally, increased from 14% in 1980 to 23% in 1997, thereafter staying constant), about 26% of the European Community's CO_2 equivalent emission (Wijkman, 2005), and cars and light trucks contributed about 20% of the total US emissions of CO_2 (and growing at a rate of 1.9% per annum (Bandivadekar and Heywood, 2004).

[6] As one example of many, 'lean-burn' spark ignition engines have approximately 10% better thermal efficiency and emit greatly reduced NO_x emission than stoichiometrically fuelled engines (Lumley, 1999). However, the reduction is sometimes insufficient to meet legislative limits and therefore many manufacturers operate the engine stoichiometrically, under which condition 'three-way' catalysts can effectively reduce NO_x to nitrogen and oxygen, nevertheless thereby sacrificing energy.

[7] There are, worldwide, strong legislative constraints that apply to (c) (for exhaust emission of CO, unburned hydrocarbons HC, NO_x and particulate matter (there are also evaporative emission standards but these are not the concern of this paper, having nothing to do with energy)), which are determined by reference to a 'drive cycle' (in Europe, through the colloquial title of 'Euro' amendments to the 1970 Directive 70/220/EEC and defined in g/km for passenger cars and in g/kWh for lorries; in the USA, through the 'Tier & Bin' standards of the Environmental Protection Agency). In considering energy, the drive cycle is important because it involves (i) a 'cold-start' phase and (ii) successive acceleration and deceleration phases and hence the mass of the vehicle has a bearing on the energy consumption of the ICE. These constraints apply to emissions but nevertheless, indirectly, determine some of the key scientific challenges for energy, as is demonstrated in this paper in Section 2.2.1. The energy requirements of ICEs also depend to an important extent on a wide range of 'boundary conditions' (these boundary conditions include customer acceptance (e.g. the increase in the appeal of 'compression ignition' ICE based on diesel fuel in the European market), traffic congestion, the age of vehicle stock and the proportion in the stock of spark ignition and compression ignition ('gasoline'vs 'diesel'-fuelled) engines in a country's fleet, the details of the mode of personal, public and freight transportation (which is important, for example, in the variation of the temperature of the powertrain during the journey), fiscal—or other—incentives for a particular type of fuel (e.g. diesel, gasoline, low sulphur, bio-derived) or type of ICE (e.g. hybrid powered)) derived from the transportation requirements specific to each country, so that a relevant metric includes the energy consumed (or mass of CO_2 emitted) per passenger kilometre. An example of relevance to this paper is the proportion of diesel and gasoline ICEs within the European passenger fleet, which differs from country to country and also with time: the diesel-powered vehicle, for comparable performance, is more energy efficient. In contrast, the USA passenger fleet is made up almost entirely of gasoline ICEs. The consideration of these 'boundary conditions' is outside the scope of this paper.

[8] These challenges are met in the context of ICEs in the service of road transportation and direct, but arguably weak, legislative constraints on this use of energy exist, in the USA, to a limited extent for (a) through corporate average fuel economy regulations in the USA: currently, targets apply for (a) in the UK and, for the European Union, to (b) through the Public Service Agreement target on greenhouse gas emissions in the UK, which requires a reduction in greenhouse gas emissions of 12.5% below 1990 levels by 2008–2012 in line with the Kyoto Protocol and a move towards a 20% reduction in CO_2 emissions by 2010, based on 1990 levels. The European Automobile Manufacturers Association has agreed (European Communities, 1999) to 'achieve a CO_2 emission target of 140 g/km CO_2, for the average of their new cars sold in the Community … by 2008. … [and to] evaluate … additional fuel-efficiency improvements … towards the objective of 120 g/km CO_2 by 2012…'.

[9] For example, friction reduction, engine control, combustion improvements, volumetric efficiency improvement, etc. Historically, these have been responsible for a linear 0.5% improvement in gasoline power to displacement ratio (Weiss et al., 2000).

[10] A car comparable to, say, a 1.6 l 77 kW VW Golf in terms of curb weight, drag coefficient, frontal area, tyre radius and inertia.

[11] The criteria include set performance for, e.g., acceleration times for 0–50, 0–100, 80–120 km/h in a given gear and range) and energy consumption over a given drive cycle (e.g. the new European drive cycle). To meet the performance criteria, the engine displacements for the CNG-PISI and the DICI are about 20% larger than the gasoline-fuelled PISI engine. In contrast, the maximum power output of the gasoline DISI is about 10% smaller than the gasoline PISI. As a further consequence, the mass of the vehicles are different, typically heavier by 5% and 7.5% for the diesel- and CNG-fuelled vehicles relative to the gasoline-fuelled PISI engine. All these factors affect the energy requirements of the engine over the drive cycle.

[12] Specifically, indicated efficiencies may rise from 0.38 to 0.41 for DISI engines, and friction mean effective pressure decrease from 165 to 124 kPa for all SI engines, by 2020 (Weiss et al., 2000).

Table 1
Summary of ways to improve energy consumption of ICEs

Type	Indicated efficiency	Mechanical efficiency	Volumetric efficiency	Combustion efficiency	Density of incoming charge	Fuel:air ratio	Emissions	Other remarks
Hybrid ICE		Increased electrification of auxiliaries						Improvement in storage of energy and braking power (including by flywheel, by ultra capacitors, by batteries)
PISI	Stratified charge (due to lean-burn effect);[a] variable compression ratio (latter up to 25% gain)	Material and lubrication improvement	20% throttle-minimised engine by: variable displacement, multistroke, downsizing+supercharging, load control by variable valve train	Variable valve train to control residual gases	Variable turbine geometry and improved compressor technology	Direct injection[b]	Additional NO_x after treatment may be required, NO_x purging and sulphur regeneration; 2–4% of fuel consumption	Combustion systems tailored to H_2 and natural gas
DISI	Direct injection (lean-burn effect on ratio of specific heat; higher knock resistance); minimised heat loss	Reduction due to high pressure pump	Unthrottled engine; mixture cooling	Deterioration of combustion at high loads/speeds, denying fuel economy, unless homogeneous charge is used			Additional NO_x after treatment may be required, NO_x purging and sulphur regeneration; 2–4% of fuel consumption	
CAI/HCCI	Higher compression ratio relative to PISI but lower than DICI			Variable valve train to control residual gases, through negative valve overlap			No need for expensive or heated catalysts? Limited to light loads?	HC and CO emissions, control of transients, ignition timing, idling, low energy exhaust prohibits turbo-charging, part-load application
Light-duty CI	Reduce effective compression ratio by ‘early intake valve closing’						DPF and NO_x control may be avoided by use of advanced fuel injection systems (e.g. split injection systems) non-thermal plasmas for NO_x	
Heavy-duty CI	Low compression ratio for emission improvement	Lower friction; decoupling auxiliaries from the crank train by using auxiliary power units	Downsizing	Increase combustion efficiency by altering effective compression ratio using variable valve train; improved fuel injection systems			Favour inc. NO_x, low part (size and number), low fuel consumption, NO_x adsorber requires injection of fuel; DPF $\approx 3\%$ fuel penalty; bio-fuels have low sulphur; combination of NO_x and particle trap, H_2S, N_2O, NH_3, aldehydes	Transmission (automate manual transmission, CVT, dual clutch: engine management systems and sensors (cylinder pressure, ion sensing, position sensors) and actuators

[a] The stratified charge using a PISI would be obtained in the manner used by Honda (VTEC) or Toyota (VVT).

[b] Direct injection enables the use of gasoline direct injection (GDI) technology, which ultimately leads to improved energy consumption.

Table 2

Average energy consumption[1] over the NEDC[2] for a mid-sized passenger car ICE vehicle 2002–2010 and for 2010+ hybrid vehicle, adapted from Edwards et al. (2006a–c)

	Baseline[3] 2002 conventional (MJ/100 km)	Evolved 2010 conventional (MJ/100 km)	2002–2010 conventional improvement (%)	2010 hybrid vehicle[4] (MJ/100 km)[5]	Improvement: hybrid and total[6] (%, %)		Hybrid-specific ICE[7] (1.28 l) (MJ/100 km)
PISI[a]							
Gasoline	223.5	190.0	15	161.7	14.9	27.7	152.9[8]
Ethanol (neat)	223.5	190.0	15				
Gasoline blend[9]	223.5	190.0	15				
LPG[b] bi-fuel	223.5	190.0	15				
CNG[c] bi-fuel	226.9	188.3	17				
CNG dedicated[10, 11]	222.8	187.2	16	139.4[12]	25.5	37.4[13]	
Hydrogen (comp[14])[15]	–	167.5	–	148.5			
Hydrogen (liquid)	–	167.5	–	141.4	15.6	–	
DISI[d,16,17]							
Gasoline	208.8	187.9	10	163.0	13.3	21.9	
Ethanol (neat)	208.8	187.9	10				
Gasoline blend	208.8	187.9	10	163.0			
DICI without DPF[e,18]							
Diesel	183.1	172.1	6	141.1			
Bio-diesel (neat)	183.1	172.1	6	141.1			
Diesel/bio blend[19]	183.1	172.1	6	141.1			
DME[f,20]	183.1	172.1	6	141.1			
Synthetic diesel	183.1	172.1	6	141.1			
DICI[g] *with DPF*[21, 22]							
Diesel	–	176.7	3.5[23]	145.6	17.6	20.5	
Bio-diesel (neat)	–	176.7	3.5[23]	145.6			
Diesel/bio-blend	–	176.7	3.5[23]	145.6			
DME	–	–[24]	3.5[23]	–			
Synthetic diesel	–	176.7	3.5[23]	145.6			

Notes:

1. The figures in the table are quoted to the same number of significant figures as the original report. The variability, quoted in Table 3, however, is estimated by the authors as lying between ±1% and ±5%, so the numbers in this table should be read to, at best, three significant figures.
2. New European drive cycle.
3. The key points for the 2002 baseline column are that:
    - The baseline (2002 figures) shows the well-known result that compression ignition engines are substantially more energy-efficient than spark ignition engines. Specifically, the DISI and the DICI have 10% and 20% less consumption, respectively, than the PISI.
    - The CNG bi-fuel (i.e. an engine capable of burning CNG and gasoline) and CNG-dedicated engines have slightly different consumption from the other ‘gasoline-like’ fuels (note that in this study the other fuels were deemed not to have any effect, positive or negative, on the energy efficiency of the engine).
    - The estimate of the variability of the energy consumption is given in Table 3: note that it is reported primarily by the fuel type rather than by the engine technology. The magnitude of the variability has a large range, for reasons explained in associated notes: these magnitudes apply, *mutatis mutandis*, to the 2010 estimates as well.
4. Weiss et al. (2000) report a simulation in which a conventional 2010+ production spark ignition SI engine (with the exception of the CNG PISI, which was downsized in the hybrid application and which reversed the exceptional ‘upsizing’ that was required for its performance to be acceptable to customers in 2002) and compression ignition (CI) engines were incorporated, unaltered, into a parallel hybrid powertrain optimised for energy efficiency benefit using a 14 kW electric motor (which represents 15% of the total available power, an optimisation for highway operation. The authors report another simulation for a 30 kW electric motor and a downsized 62 kW ICE, which is more appropriate for city driving because of better energy capture through regenerative braking) with 42 V lithium/ion batteries subject to four parameters (the state of charge of the battery, the recharge mode and the minimum vehicle speeds below which the thermal engine was off while recharge was, or was not, activated). The total efficiency improvement of the hybridised vehicle, and the proportion due to hybridisation alone, are given separately in this table (specifically, the authors note that: ‘…The hybrid architecture and downsizing/turbo-charging (considered for the 2010 conventional configurations) are two routes that allow the thermal engine to be operated in a domain of better efficiency. The benefits are therefore not cumulative…’).
5. Improved 2002 Conventional Engine: see text.
6. Some elements of the improvements to conventional engine technology considered for 2010 have been already included in the hybrid architecture and must not be counted twice.
7. This engine develops 62 kW.
8. The ≈6% improvement due to the use of a hybrid-specific ICE is ‘… assumed to be applicable to all powertrains and fuel types covered by the study with no assumption about the technical feasibility …’
9. Ethanol 95/5: weak blend fuels imply little or no modification.
10. CNG has a high ‘knock resistance’ (octane number) and the compression ratio can be raised to 12.5:1, corresponding to an energy-efficiency increase of 9% over the gasoline reference. Unfortunately, the maximum power per unit engine displacement is reduced by about 20%, partly because the air is displaced by the volume of the natural gas, so that a higher torque is required to meet acceleration performance criteria and this entails increasing the displacement of the engine to 1.9 l, which increases fuel consumption—as does the heavier CNG tank.
11. The extra 1–2% efficiency is ascribed to the better ability of mixing the natural gas fuel with air, which improves cold-start combustion.
12. The energy consumption of the CNG hybrid is, according to this table, slightly more economical than the DICI hybrid, a result that is not in accordance with an alternative estimate (MIT study) which places the CNG hybrid and gasoline hybrid on a par. The difference is that the MIT study considers the situation in 2020, where (presumably) the ICE for hybrid use is a dedicated design, as in the last column of this table.
13. Hybridisation is particularly favourable for CNG PISI energy consumption because electric assistance allows performance criteria to be met with a 20% reduction in the displacement of the ICE as compared to a 2002 base, thereby delivering the full benefit of CNG’s higher octane rating and associated higher compression ratio.
14. Compressed gas.
15. The engine design for the hydrogen ICE was considered to be designed anew (i.e. not evolved), making use of a 77 kW, 1.3 l downsized, turbo-charged engine. Its apparent superiority among PISI engines in the 2nd column is somewhat misleading: it is closer to the hybrid-specific downsized PISI in the rightmost column of this table, which is a 62 kW 1.28 l gasoline engine and which is yet more economical than the hydrogen ICE.
16. The DISI engine has lower fuel consumption than the PISI because it runs in lean-burn mode.

Table 2 (*footnote continued*)

17. For the DISI configuration, the following assumptions were made:
    - ○ Below 50 °C, the engine operates in 'homogeneous' mode, at stoichiometric conditions (not 'lean burn')
    - ○ Above 50 °C, in a range of low-speed, low-to-mid load, the engine is under lean stratified conditions, with the typically lower fuel consumption of DI engines.

18. EURO III diesel vehicles are assumed to be fitted only with an oxidation catalyst.
19. Diesel and bio-diesel 95/5: bio-diesel blends up to 5% with conventional diesel fuel can be burned in standard diesel engines.
20. A custom fuel tank and injection system is required for DME.
21. Diesel particulate filter.
22. EURO IV diesel vehicles are likely to be equipped with a DMP.
23. Relative to the 2010 engine without DPF.
24. DME results in few particulates and so would probably not require a particulate filter.

Key

a. Port injection spark ignition.
b. Liquefied petroleum gas.
c. Compressed natural gas.
d. Direct injection spark ignition.
e. Diesel particulate filter.
f. Di-methyl ether.
g. Direct injection compression ignition.

between 15% and 10% over a period of a decade. The former estimate, at least, is broadly comparable[13] to the prediction in Weiss et al. (2000) for a decade's worth of improvement

- 2010 PISI/DISI engines, which will have efficiencies[14] only 10% worse than unfiltered[15] 2010 DICI engines, and less than that if the 2010 diesel has a diesel particle filter (DPF) fitted
- improvements in CNG engines, which will improve their 2010 energy consumption beyond PISI and bring these close to that of a 2010 diesel. (Note that, in 2002, CNG-powered vehicles were slightly less efficient[16] than equivalent PISI vehicles at the time.)
- the design of a hydrogen-fuelled PISI engine with a 'tank-to-wheel' efficiency close to that of a 2010 diesel engine.[17] The NO_x emissions, which would otherwise be high because of the high flame temperature of a hydrogen-fuelled flame, are to be kept low by burning at lean mixture strength
- a ratio of the best to the worst consumption in Table 2 of 60%. This is also commensurate with the estimate of Weiss et al., who, over a slightly longer time horizon of 2020, predict a reduction of 53% (Table 3).

The figures given above are also comparable to those reported in Anon. (2003).

Table 3
Estimated energy consumption variability 2002 ICE vehicles (Edwards et al., 2006a–c)

Fuel/ignition mode	Overall variability (%)
Gasoline	
DISI	−4/4[a]
Gasoline blend	
PISI	−1/1[b]
DISI	−4/4[c]
LPG	
PISI	−2/2[d]
Diesel	
DICI	−3/3
Diesel blend	
DICI	−3/3
CNG PISI[e]	
Bi-fuel	−5/3
Dedicated	−6/3

[a] Due to cold-start consumption of DISI engines.
[b] The impact of the latent heat of vaporisation is not fully known.
[c] Due to cold-start consumption of DISI engines.
[d] Uncertainty from extrapolation from PISI.
[e] Uncertainty partly from extrapolation from PISI: the uncertainty for CNG fuels due to cold start is expected to be smaller because of the better mixing between the gaseous fuel and the air.

1.3. *Key scientific advances to 2010+*

This sub-section introduces several 'technologies' for the reduction of the energy requirements of ICEs. Regrettably, the improvements are not completely additive when multiple technologies are built into a powertrain, nor can the cost of multiple technologies be borne by the smaller, lower-cost vehicles making up the major proportion of the European fleet (and hence responsible for the majority of fuel consumed). These two statements must be borne in mind when assessing the likely effect of these technologies on the energy consumption of the European fleet of vehicles.

1.3.1. *Spark ignition engines*

For a vehicle powered by PISI engines, the main improvement to energy efficiency comes from so-called 'downsizing',[18] a trend

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[13] For the 'evolved baseline' PISI, 'fuel consumption and greenhouse gas emissions [will] have been reduced by about a third [by 2020]': the authors estimate that there is an uncertainty of about ±10% on this figure, which is the most confident prediction that they make.

[14] Specifically, DICI engines may have indicated efficiencies in the order of 0.52, and with friction mean effective pressure decreasing from 180 to 153 kPa, provided that the associated NO_x emissions can be dealt with (Weiss et al., 2000).

[15] That is, no diesel particulate filter would be fitted.

[16] Specifically, the indicated efficiency is expected to be 0.44 (Weiss et al., 2000) for CNG-dedicated engines by 2020.

[17] Note, however, the 'well-to-wheel' efficiency is poor by comparison to direct use of natural gas (the presumed source for hydrogen in the next decade). See also Table 5.

[18] So that, on an average, much of the energy lost to pumping work past the throttle of the engine is minimised. The displacement of the gasoline engine can be reduced by about 20%, with the level of torque required for the more aggressive acceleration being provided by turbo-charging whenever this level of performance is required.

that is already in place, and one can have considerable confidence that this advance will occur. Downsizing can be achieved through, e.g. hybridisation, discussed below, or through 'cylinder deactivation'.[19] Both trends are starting to be evident, the latter in the USA, and will be facilitated by increasing the flexibility of valve train actuation. The advantages of 'de-throttling' a spark ignition (SI) engine can also be achieved through fully variable valve timing (4% fuel economy) and lift: electro-mechanical camshaft-based systems devices are available that currently deliver less than 8% fuel economy. The challenge is to reduce their cost and increase their flexibility, probably by superseding these with electro-hydraulic or perhaps electro-pneumatic, actuators[20] (for example, cargine.com).

For a vehicle powered by DISI engines,[21] the main improvements to energy efficiency could come from a variety[22] of measures, including:

- extending the power range over which the engine can operate in 'lean burn' mode. This will be a considerable challenge, particularly taking into account that the regulations on particulate emissions are likely to become ever more stringent
- increased compression ratio relative to a PISI (Heywood et al., 2004), which will require improved management of the air–fuel mixture distribution in the cylinder at ignition.

The extent to which DISI engines will be able to develop commercially depends on reducing their relatively higher cost, which arises from their use of advanced injection technology, the need for additional NO_x after-treatment, and on managing the reduction in mechanical efficiency due to their use of a high-pressure fuel pump.

1.3.2. Compression ignition engines

The indicated efficiency may rise by about 7% due to increased boosting and improved combustion control. The long-term challenge is that diesel vehicles may have to be equipped with a DPF to meet emissions standards (Euro IV), in which case there will be a loss due to pumping and regeneration. The current assessment by Edwards et al. (2006a–c) is that the efficiency loss associated with periodic regeneration is about +2.5%, which recent development has reduced from an estimate[23] in 2003 of about 5%. It will be challenging to reduce that number still further. There is, however, some hope that, by about 2010, light-duty diesel engines (for use in vehicles up to inertia weight of about 1800 kg (Anon., 2003)) may escape the fitting of a DPF, provided that in-cylinder combustion can be developed to the point that the Euro IV emissions standard is met. Although great strides have been made in the past half-decade, particulate emission legislation may be a hard goal to meet by in-cylinder measures alone in the long run.[24] The scientific challenge will be met, partly, by improved accuracy of computational fluid dynamics (CFD)[25] and experimental investigations including those based on optical (usually laser-based) techniques for probing 'in-cylinder' processes.[26] Whether CFD methods are likely to remain aids to flow visualisation rather than fully predictive of combustion performance remains to be seen and the relative value of CFD vis à vis optical experimental methods is a matter of debate. To these should be added the techniques from, for example, tribology and the application of 'mechatronics'. These are subjects that are traditionally developed in departments of engineering science at universities and the 'evolved baseline' implies development and advances in these key sciences that will match the progress made in the last three decades. The majority of these techniques will continue to require graduate scientists and engineers educated at the post-graduate, and probably doctorate, level to transfer the advances to industry and commerce.

1.3.3. General energy management

Idling represents about 7.5% of the total fuel consumption over the regulatory emission test cycle, and being able to 'switch off at idle' thus represents a large potential reduction in energy consumption.[27] Improved design of the gearbox[28] can assist in the process of downsizing a PISI engine by transferring the requirements to higher engine loads. Other measures also exist.[29] Much of the improvement for DICI engines is expected to arise from improved lubrication, which has already delivered significant reduction in energy consumption through the decreased

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[19] Whereby, at low power requirement, some cylinders do not participate in the four-stroke cycle through advanced control of the engine.

[20] There is a variety of electro-pneumatic designs: cargine.com features a cam-less variant. Electro-magnetic—i.e. cam-less—valves have also been under development for several years: the challenge here is to reduce their power consumption. A particular prize of a cam-less engine would be that there would no longer be so stringent a demand for the lubrication of sliding contacts, which would make the preparation of lubrication oil easier.

[21] For vehicles powered by DISI engines, much of the advantage in the reduction in throttling is already included in the current designs.

[22] For example, improving the cold start. In part, these improvements may become more likely by improvements to gasoline direct injection technologies (variable rail pressure, piezo injectors).

[23] Edwards et al. (2006c).

[24] An interesting possibility is that DME-fuelled vehicles would not need such a filter because that fuel has a low sooting propensity. Whether, and indeed if, DME gains widespread use or remains a niche fuel, perhaps for buses in densely populated urban areas, is hard to predict.

[25] Numerical solutions of modelled versions of 'first principles' equations for, e.g., the conservation of mass, momentum, energy and for chemical reaction ('combustion') and two-phase flow for fuel atomisation.

[26] These processes include gas motion, atomisation of the liquid fuel and the mixing of the vapour with the oxidant, ignition and flame front propagation, and the production and destruction of pollutants.

[27] Table 2 includes a 3% saving for all 2010 ICE configurations on the assumption that some such strategy is adopted. A key challenge is to reduce the energy lost, and the emissions generated, during the 'start' phase and to take into account the fact that the engine block will cool down during the 'stop' phase.

[28] Currently, a manual transmission is about 94% efficient and a four-speed automatic is 70–80% efficient (Ellinger et al., 2001). So-called automated clutched transmissions can have an optimised gear shift strategy leading to improved fuel consumption and have about 88% efficiency. The next stage in this process is the use of continuously variable transmissions (CVT). Current CVT designs have high power losses: the target is 88% efficiency (Weiss et al., 2000). Currently achievable energy savings range from +8% to even deteriorations of approximately 2%, depending on the implementation. It is clear that there is a substantial benefit to be gained from a breakthrough in this topic and there is intensive research worldwide.

[29] These include

- optimised operation of auxiliaries on demand (e.g. water pump, power steering pump, etc.), including electrical powering of the auxiliaries. Electrical power consumption is currently about 300 W but may rise to as much as 1 kW, or higher, in 2020. Auxiliary power units avoid many issues with batteries and electrical energy storage to supply base power needs. Linear, possibly free-piston, engines (combined with linear electric motor technology) or rotating types of combustion engine are suitable, as are—potentially—solid oxide fuel cells.
- reuse of losses, such as recuperative braking, exhaust gas heat exchange for accelerated warm up, etc. Use of the latter may account for a 2% reduction in energy consumption.
- improved electric generators (an increase of the average efficiency from the usual value of 55% to 75%) lead to a reduction in energy consumption of 2% for all engine technologies.

viscosity of modern synthetic multigrade oils, in conjunction with better additives such as friction modifiers. The continued development of future lubricants will, in part, be a contest with the need for reduced emissions from phosphorus-, sulphur- and ash-containing compounds, which are, however, tribologically desirable. In addition, the use of diamond-like coatings and 'textured surfaces', such as dimples on piston skirts, can be expected to deliver improvements although the transition to materials such as aluminium and silicon, which are required for other reasons, will make it harder to provide continued improvement in lubrication.

The continued development[30] of turbo-charging is central to the large improvement in efficiency of PISI and DISI engines through downsizing and thermodynamically the use of exhaust gases for this purpose is preferable. Much remains to be done on turbo-charger design, particularly on surge at low speed, on transient performance—particularly using turbine vanes—and on enhanced energy extraction from the highly pulsating flow emanating from the engine exhaust.

1.3.4. Hybridisation

Tentative commercial steps in hybridisation have already taken place, partly to recover energy that would otherwise be lost during braking ('regenerative braking') and partly to improve 'launch' from standstill. Table 2 quantifies the substantial savings ($\approx$17% for DISI engines, for example) in energy that hybridisation of 'standard' production engines is likely to produce for stop-start or 'hilly' driving conditions[31] and, of the further energy savings, of about 5%, to be made if a specially sized ICE is used[32] (Edwards et al., 2006a–c). Continued progress in this direction depends on the integration of a 'starter generator' and the development of an associated control system, the development of new transmissions, of clutches and of large electrical machines, all of which are expensive and not yet well developed. The extent to which progress will be made also depends on the development of energy storage systems,[33] primarily of batteries and super-capacitors.[34] All these items imply increased cost, weight,[35] reduced reliability and increased complexity, none of which is desirable, Hybridisation's full benefits may not be achieved without (i) adjustment of driving style to suit (there are increasing reports of in-service fuel economy rather less than recorded in testing) and (ii) some (non-technical) incentives to mitigate the capital cost, which is unlikely to be trivial, even with mass-market appeal (the capital cost of a diesel engine is several tens of percent higher than that of the comparable SI engine, for similar reasons).

2. Future advances: to 2050 and beyond

2.1. Key challenges

The key challenges over the longer term are posed by the development(s) in:

- emission legislation and emission control
- new fuels, their availability and their composition
- improved combustion
- advanced concepts for energy saving.

2.2. Key scientific advances

2.2.1. Energy-efficient emission control

There will be vigorous investigation into the reduction of the energy penalty associated with the after-treatment of NO_x and particulates generated by the diesel engine, particularly for so-called 'heavy duty' engines. The gain will be twofold, because the ability to remove NO_x from exhaust emissions will permit diesel engines to be re-calibrated for better energy consumption which, at least with conventional diesel combustion, implies higher NO_x levels. However, it is likely that legislation for particulate matter will in the future continue to limit the amount of emission, with the possibility that number-based, rather than mass-based, limits become the measure of pollution. Were this to happen, it is likely that the energy penalty associated with existing technologies[36] would increase. In addition, legislation for aldehydes is likely to appear after 2010, particularly if fuels with high ethanol content come into widespread use.

The disadvantages of the existing systems are so great that these are likely to attract intensive research effort to find and develop improved catalysts and to deliver a given level of after-treatment with reduced pressure loss and hence improved energy

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[30] However, the drawbacks of conventional turbo-chargers are that these have poor 'transient' throttle response and poor low-end torque. Thus bi-sequential turbo-charging, or electrically assisted turbo-chargers, or combined systems of turbo- and electrically driven supercharger, may be important in future. Electrically driven auxiliary machinery can, however, be inimical to the energy consumption of an ICE, as explained later in this paper: and unless special designs are developed, the attaching of an electrical machine to a turbo-charger can be a retrograde step in that the inertia of the combination increases greatly relative to a conventional turbo-charger and this is undesirable.

[31] For example, Heywood et al. (2004) report that hybridisation over the US06 drive cycle, which represents higher speeds and aggressive decelerations, results in only a 5% improvement in energy consumption, while operation over the Japanese 15-mode cycle results in a 50% improvement.

[32] The addition of a 14 kW electric motor to conventional 2010+ production engines results in a power-to-weight ratio for the vehicle in excess of the standard power-to-weight ratio (for a passenger car) of 75 W/kg. If the ICE is further downsized to recover the 75 W/kg figure due to the combined output powers of the ICE and electric motor, further savings seem to be possible.

[33] Hybridisation increases vehicle mass by about 10% when allied to the conventional 2010+ ICE.

[34] In terms of the power density, recharge time, weight.

[35] The optimisation of flywheels and hydraulic storage systems, in terms of improved weight, volume and noise would also be valuable.

[36] For particulates, the continuously regenerating trap (CRT™) is an elegant concept which currently, however, requires (i) low sulphur fuel ($<$10 ppm wt/wt), which is not yet available widely and (ii) exhaust temperatures above about 250 °C which is not always the case (the use of a catalytic additive, such as cerium, is effective but is expected to lead to ash-clogging of the DPF after about 120,000 km and is not considered a viable solution for the long-term future). Thus DPFs require periodic regeneration (the removal—by 'burning off'—of the accumulated matter on the filter by their conversion to water and CO_2) every few hundred kilometres. The energy loss comes from:

- the pumping pressure loss due to the pressure drop across the DPF as the particulate matter clogs the filter
- the need to raise the temperature of the exhaust gas to the soot ignition temperature, either by injecting extra fuel in the exhaust gas with the promotion of its combustion by a catalyst or by retarding the start of in-cylinder injection (which may result in the unwanted dilution of the lubrication oil).

  For the reduction of NO_x emissions, the drawbacks of the two current technologies are:
- the continuous selective catalytic reduction (SCR) of NO_x using urea implies an energy penalty for the manufacture of urea (a similar system makes use of diesel fuel instead of urea, in which case the energy penalty is explicit)
- the NO_x adsorber catalyst (or accumulator-type, or traps), which requires not only the operating window to remain at 250–450 °C but also the regeneration of the filter every few minutes by the deliberate generation of a reducing atmosphere above the catalyst, which can be achieved through either retarded injection of fuel into the cylinder and intake air throttling or by direct injection of fuel into the exhaust system, upstream of the adsorber. The need to regenerate increases energy consumption, causing a penalty of about 10%, of the ICE (Anon., 2003). In addition, this catalyst technology is sensitive to sulphur in the fuel and may require sulphur regeneration every 10,000 km or so (Anon., 2004).

Table 4
A selection of ‘alternative’ future fuels, adapted from Edwards et al. (2006a–c)

Gasoline substitute fuels (for spark ignition engines)	Diesel substitute fuels (for compression ignition engines)
Ethanol	Bio-diesel[a]
Gasoline/ethanol blend	Fischer-Tropsch diesel ‘synthetic’ diesel[b]
MTBE[c] and ETBE[d]	DME[e]
LPG[f] or other GTL[g]	
CNG[h] and CBG[i]	
Hydrogen	

[a] For example, fatty-acid methyl ester.

[b] Also known as synfuel and sunfuel, depending on the derivation (synthesis or solar power) of the feedstock. Diesel fuel from Fischer-Tropsch (F-T) synthesis or other GTL processes for converting natural gas is better than current petroleum diesel with respect to its high cetane number and zero sulphur content.

[c] Methyl tertiary butyl ether, a high-octane blending component for gasoline but was withdrawn in the USA due to concern about water contamination.

[d] Ethyl tertiary butyl ether.

[e] Di-methyl-ether, which is similar to LPG in that it liquefies at moderate pressure.

[f] Liquefied petroleum gas.

[g] Gas-to-liquid.

[h] Compressed natural gas.

[i] Compressed bio gas.

Table 5
Energy use and greenhouse gas emissions during the fuel cycle (per MJ of fuel delivered to the vehicle) (Weiss et al., 2000)

Fuel	Energy use		Greenhouse gases
	MJ/MJ[a]	Efficiency (%)	(gC/MJ)
Gasoline	0.21	83	4.9
Diesel	0.14	88	3.3
CNG	0.18	85	4.2
Fischer-Tropsch diesel	0.93	52	8.9
Methanol[b]	0.54	65	5.9
Hydrogen[c]	0.77	56	36

[a] Total energy consumed originating from raw materials or other energy sources per MJ which is delivered to the vehicle tank.

[b] Methanol from natural gas conversion.

[c] Hydrogen from natural gas reforming.

consumption. In addition, a variety of novel approaches may appear, for example:

- The combination of a NO_x trap and particle trap into a single unit would reduce the fuel consumption penalty. One such system has already been announced.
- The use of ‘closed-loop’ control, based on a cheap NO_x sensor, to ensure that regeneration takes place only when it is needed.
- The development of non-thermal plasma technology to oxidise NO to NO_2, which may be more energy efficient, have a wider operating window than current approaches and is sulphur-tolerant. The same technology may be able to:
    - ○ generate ‘on-board’ hydrogen-rich gas, or light hydrocarbons, for the regeneration of NO_x absorber catalysts
    - ○ generate ammonia ‘on board’, using NO as a feedstock, for the selective catalytic reduction (SCR) reaction with NO_x.

2.2.2. Changes in fuels

Reserves of traditional oil resources must become depleted and more expensive to recover. This is unfortunate, as no other fuels can match the energy density so advantageous for transport. In the future, it is likely that, in addition to the conventional petroleum-derived fuels, namely gasoline and diesel, ‘alternative’ fuels will become commercially available for ICEs and road transportation in the future, as listed in Table 4. These alternative fuels are also low-sulphur fuel (<10 ppm wt/wt), which improves catalyst life and performance and hence, indirectly, improves energy consumption. However, these ‘alternative’ fuels must be compatible with lubrication systems for, e.g. emissions of particulates.

Of the petroleum substitutes, CNG[37] has a higher octane number than does gasoline[38] and hence CNG-dedicated engines can have higher compression ratios and so have higher indicated efficiencies.[39] However, if it were considered sensible to devote more of the world’s (greater than oil) natural gas reserves to transport, it might be more sensible to employ the gas to liquid technologies now entering large-scale production than to accommodate the weight/storage/distribution disadvantages of CNG. Of the diesel substitutes, dimethyl ether (DME) is notable in that it has a reduced propensity to generate soot and therefore use of this fuel will prevent the energy consumption associated with particulate removal. Hydrogen, which will be mostly non-renewable and derived from electrolysis until 2050, is more correctly a ‘vector’ (means of energy transport), than a fuel. Hydrogen (on a ‘tank-to-wheels’ basis) is an excellent ICE fuel, some of the benefits of which can be achieved by on-board reforming of conventional fuels. There are no particular problems with operating engines on hydrogen—the difficulties lie with distribution and on-board storage (also increased weight, associated with its storage, counters one of the principal means of improving overall vehicle efficiency).[40] In addition, hydrogen, should it become available in large quantities, may require substantial energy loss for after-treatment to remove NO_x from the exhaust, even from lean-burn operation—the latter improving the energy consumption of the engine.

Bio-ethanol is conspicuous by its absence from Table 5, primarily because the reference from which these data are drawn did not include this fuel. However, it is not straightforward to quote a value from another source because there is a bewildering variety of estimates for the magnitude of the saving in terms of ‘energy use’ and of greenhouse gas emission. Table 5 is derived from a group at MIT, and the same group, in a separate report (Bandivadekar and Heywood, 2004),[41] cite work in the early 1990s that claims that bio-ethanol ‘… has a potential to reduce the full fuel-cycle emissions of greenhouse gas emissions in g/km of CO_2 equivalent by as much as 40–70%’. This apparently extravagant range is supported by recent arguments (Edwards et al., 2006b, Figs. 5.1.5–1). The range derives from the nature of the ‘feedstock’—crops grown specifically for the purpose are the least

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[37] As do, to a lesser extent, ethanol, methyl tertiary butyl ether and ethyl tertiary butyl ether.

[38] Similarly to gasoline, due to three-way catalysts, CNG has the potential for particularly low emissions and hence CNG-powered vehicles may gain market share in niche applications, such as the powering of urban buses, in the medium term.

[39] However, CNG is a gaseous fuel and hence the ratio of power-to-engine displacement is unfavourable by comparison with a liquid fuel (this is also true of hydrogen, entailing high-pressure ratio-boosting systems to achieve the required power density): the consequences for energy consumption are important when considering vehicle hybridisation and this has been considered under that heading.

[40] Note added in 2008 revision: a recent paper (Schäfer et al., 2006), supports the assertion that, even with a fuel-cell power plant, there may be no advantage over an ICE-hybrid engine.

[41] Reference added in 2008 revision.

advantageous.[42] The details of the complex calculation are given (Edwards et al., 2006c). Allowance is made for many matters, including the fact that the carbon 'gain' has to be made against a 'reference crop', which is argued to be grass: reporting further details is beyond the scope of this paper.

The introduction of alternative fuels may raise the possibility of fuels that are better suited to the novel combustion systems, such as homogeneous charge compression ignition (HCCI) mentioned below.

A 'well-to-tank' analysis of the energy requirements of ICEs using 'alternative fuels' is outside the scope of this science review, particularly with regard to biofuels (Elsayed et al. (2003) is a recent review on this matter). One point on this matter, however, needs comment. Table 5 shows that on the basis of the metrics 'energy use and greenhouse gas emissions during the fuel cycle (per MJ of fuel delivered to the vehicle', (Edwards et al., 2006a–c) suggests that non-conventional fossil-derived fuels have a larger greenhouse gas emission than do conventional fuels and that vehicles powered by fuel cells using non-renewable hydrogen do not necessarily offer a well-to-wheels improvement in efficiency over the best ICE hybrid technologies. Nevertheless, ethanol (which is not included in Table 5) has a significant and increasing role in substituting gasoline and the trend is likely to continue—if only for strategic, or 'security of supply', benefits. Engines of higher compression ratio (hence expansion ratio and higher efficiency) are available in some markets to suit neat ethanol and ethanol/gasoline blends. During 'cold start' (particularly for northern European countries in winter) however, the emission of aldehydes—compounds which are inherent to the combustion pathway of ethanol and which are noxious but for which there is (at the time of writing) no legislative limit—will need strong mitigating measures beyond conventional three-way catalysts.

2.2.3. *Improved combustion*

Over the long term, there is hope that ICEs combining high efficiency with low emissions from the cylinder[43] of particulates and NO_x can be designed by radical change to the combustion process (sometimes known as HCCI). The principle is to use a close approximation to a four-stroke Otto cycle powered by the auto-ignition[44] of a globally ultra-lean,[45] partially premixed charge,[46] with the necessary rise in temperature produced largely through compression work, implying a compression ratio which is higher than current gasoline engines. This combustion process is omnivorous in terms of fuels[47] provided that certain restrictions on octane and cetane number are respected. The attraction of this mode of combustion for those investigating diesel engines is that it promises to do away with filters and NO_x traps which, for the foreseeable future, come with significant practical disadvantages. The advantage for those investigating gasoline engines is that this mode of combustion promises substantial improvement in energy efficiency: Yang et al. (2002) have shown that HCCI engines can have specific fuel consumption, at part load, of 50% that of PISI engines and 30% less than a DISI prototype.

Research in the past half-decade or so has made impressive progress but has also shown the challenges associated with this mode of combustion. These include:

- the need to control the rates of pressure rise in the cylinder.[48] This, in turn, implies the need to
  - ○ increase the amount of fuel that can be admitted to a cylinder[49] while avoiding 'knock' and the rise in emissions. At present, this seems to be a hard problem to overcome. It may even be that its solution will require development of new fuels (of comparable total energy content) with lower heat release rate at high temperatures.
  - ○ find a way, 'in-cylinder', to limit the emission of unburned hydrocarbons and CO emissions so as to retain the thermal efficiency of HCCI combustion
  - ○ extend HCCI combustion over the whole engine map
  - ○ deliver the above while maintaining low oil consumption.
- the need to find a means to control the ignition timing, particularly with a view to control speed- and load-transients.

A related but separate topic is the development of highly premixed, low temperature combustion in diesel engines, which permits greater control of ignition timing and control of transients and the development of higher specific power than the HCCI approach, at the expense of less advantageous improvement in the emissions levels. Absolutely crucial in the context not only of this paragraph, but also of this sub-section, is the need for fuel injection equipment at high injection pressures (greater than 2,000 bar) and the ability to choose lift and speed of nozzle lift for injection rate shaping.

The exciting scientific challenge is to provide rational guidelines for meeting these challenges, based on knowledge of:

- the low- and high-temperature chemistry of combustion of fuels[50]
- the physics of 'appropriate' atomisation to promote this mode of combustion
- the flow within the cylinder

using the 'mechatronic' controls, which will become readily available (although probably not cheaply) in the next decade. For example (Anon., 2003):

- advanced adaptive and closed-loop, combustion feedback control and new sensor technologies (e.g. cylinder pressure, ion sensing, position sensors) leading to
  - ○ single-cycle control strategies
  - ○ the enlargement of the possible operation range, improved transient response and the development of suitable combustion control systems (for cycle-to-cycle control)
- variable compression ratio[51] and multi-stroke engines

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[42] Crops that can be used together with co-generation are the next most advantageous, and the most advantageous of all is the use of a left-over, sugar cane bagasse.

[43] As opposed to the post-, or tailpipe, treatment emissions.

[44] As opposed to spark ignition with gasoline fuel.

[45] By comparison with the best lean-burn gasoline direct injection engines.

[46] As opposed to the predominantly unpremixed (or 'diffusion') flame in a conventional, contemporary diesel engine.

[47] Including conventional fuels—i.e. gasoline and diesel, mixtures of the latter two, and most of the fuels in Tables 4 and 5—with a view to understanding and controlling the volatility and cool-flame properties of the fuel in conjunction with the development of appropriate standards to parallel motor octane number (MON) and research octane number (RON) ratings for conventional fuels.

[48] Certainly to limit the noise of the engine and probably to avoid knock-like damage to the piston.

[49] Which currently is undesirably low, hence limiting the brake mean effective pressure developed by the engine. In the near term, this difficulty is likely to be resolved by 'dual mode' operation, whereby HCCI is used for low-power output and conventional combustion, either spark or compression ignited, for high powers.

[50] 'Fuels' here refers to both conventional and new fuels. The chemistry needs development because this mode of combustion makes use of (i) unusual degrees of premixing of the fresh charge with diluents such as EGR of various qualities and temperature and (ii) possibly of cold-start enablers. There may be a need for the development of fuels with suitable vaporisation and ignition behaviour.

[51] The cost of the mechanism to achieve 'true' variable compression ratio is high. In practice, the Miller cycle—achieved by variable valve technology (see below in the main text)—will achieve much of the same effect without the great

- cylinder de-activation (variable displacement—switchable tappets; switchable finger followers or camless, fully variable valve train), enhanced low-pressure exhaust gas recirculation (EGR) cooling and temperature control
- increased supercharging, intercooling, electrically assisted turbo-chargers (see below for the latter topic)
- variable valve train concepts (for phase and lift) for optimised torque and transients, including the use of Miller cycles, and for variable swirl (Anon., 2003) as well as for EGR cooler and bypass operations
- advanced fuel injection systems for injection characteristics to reduce emissions; multiple nozzles and variable injection hole-size to reduce emissions; the use of injection pressures up to 3,000 bar with the ability to shape the injection rate
- currently, there are several programmes in the USA to use a range of the above strategies[52]—excluding HCCI combustion—to raise the brake thermal efficiency of a ≈350 kW engine from about 45% to 50% (Coney et al., 2004), while meeting projected 2010 US emission levels.

2.2.4. Advanced concepts

This sub-section presents four advanced concepts that represent scientific challenges of varying degrees.

The 'isoengine' operates on a new thermodynamic cycle to reach, reportedly, an efficiency of about 60%, although the concept has been developed for large (MW class) engines and has other characteristics that may not lend this engine to vehicular use. The isoengine achieves its high efficiency by the integration of three main features into its cycle. These are (i) the compression of air quasi-isothermally in cylinders separately from the power cylinders, (ii) the recycling of thermal energy from the exhaust gas, the turbo-charger and the engine cooling system into the cool compressed air and (iii) the simultaneous injection of fuel and induction of hot compressed air into the power cylinders, thus maintaining constant pressure during combustion (Coney et al., 2004). This design is unlikely to achieve its theoretical 60% efficiency in practice (just like any other theoretical cycle) and would involve increased capital cost and involve companies in major changes to their manufacturing processes, which would necessitate a long lead time.

The 'waste heat' rejected through the exhaust represents a large fraction of the fuel's energy. There have been several proposals (e.g. Nelson, 2005; for a manufacturer's perspective, see Endo et al., 2007) to use waste heat recovery in the form of a Rankine bottoming cycle.[53] Thermal efficiencies increase by about 10% (i.e. from about 29% to 32%).

Electric turbo-compounding is another way to harness waste heat: this concept can provide (Vuk, 2005) approximately a 10% increase in fuel economy, resulting in a target efficiency in an engine with turbo-compounding of 46% at the same time as a 20% increased power density. Turbo-compounding is applicable where there is steady high-duty load requirement, such as in long-distance lorries, and where there is benefit to the vehicle due to its electrification. Recent development of cheap controls, effective power electronics derived from hybridisation, the need for EGR for NO_x control (because the increased back pressure on the engine drives EGR) and the existence of high-pressure ratio turbines all make turbo-compounding an increasingly attractive proposition. A closely related concept (Millo et al., 2005) is the coupling of a turbo-charger with an electric motor/generator, which may, depending on the vehicle duty cycle, deliver up to a 5% improvement in the energy consumption, as well as providing decreased emissions during transients (typically, the motor/generator's power is less than 10 kW for a 300 kW engine). Motor assistance of the turbo-charger helps to reduce the turbo-lag and so facilitates engine downsizing. The electric machine can operate as a generator whenever it is possible to extract from the exhaust gases more energy than is necessary to reach the target boost pressure. Motor/generator turbo-charging is beneficial, provided that the driving cycle results in regeneration periods that produce and store at least as much energy as is required to speed up the turbo-charger during acceleration transients of the ICE. Thus, the maximum benefit is derived from highway and 'bus lane' duty cycles, whereas no benefit is derived from driving in heavily congested traffic.

Although the improvement of the low-speed response of turbo-chargers is a clear objective, the amount of emphasis to be placed on overcoming 'mechanical' inertia (e.g. as implied or stated in the preceding paragraph: lighter rotors, electrical and other 'assist' mechanisms) as opposed to (as hinted above) fluid mechanic problems such as surge is a matter of considerable debate. Current developments in variable compressor (in addition to more familiar variable turbines) and air intake accumulators may prove useful and will possibly appear over relatively short timescales (i.e. 2010+ rather than 2050).

It is possible that, in future, thermoelectric devices, which rely on the Seebeck effect to convert sensible heat in the exhaust gas stream (which accounts for up to about 30% of the fuel energy) and from cooling (such as the EGR cooler), might be able to increase ICE efficiency by up to about 10 percentage points (e.g. Fairbanks, 2005). The ability to realise this rests primarily with the efficiency with which a thermoelectric device can convert heat to electricity, which is determined by the material properties (the Seebeck coefficient and the electrical and thermal conductivities) used to perform the conversion. Until recently, the efficiency of conversion was poor but the prospect of 'low-dimensional' thermoelectrics, using quantum wells, super lattices, quantum wires, and quantum dots to change band structures, energy levels, and density states of electrons have increased the figure of merit by a factor of up to three. This makes it possible to hope that further development could permit the improvement of 'efficiency' (with the control volume drawn around the powertrain rather than around the heat engine) by 5–10% (Schock, 2005). In

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(*footnote continued*)
cost of a true variable compression ratio design, getting the advantages of high expansion ratio with lower compression ratio to avoid knock at high load.

[52] One manufacturer (Easley et al., 2005) estimates that improvements in efficiency are available as follows:

- 0.2% for optimisation of the trade-off between increased NO_x production by a more efficient engine and increased cost of NO_x conversion
- 0.3% for reduced heat rejection, including the use of thermal barrier coatings on the piston and on the head
- 0.9% for turbo-compounding
- 1.8% for an improved air system (series turbo-chargers; high-efficiency compressor, turbine and bearings; intercooling)
- 2.3% for optimisation of the compression ratio, of the peak cylinder pressure, of the intake valve closing timing and of the air system for proper boost.
  Another approach (Aneja et al., 2005) consists of improving the:
- advanced fuel injection system: at high-power output, strategic multiple injection timing at reduced injection pressure permits an increase in thermal efficiency while minimising the penalty in the emission of particulate matter
- optimisation of EGR cooling
- air system enhancement
- optimised combustion process, including variable swirl.
- increased engine compression ratio, increased cooled EGR rates allied to effective transient emissions control.

[53] The cycle might make use (Nelson, 2005) of a binary steam/fluorocarbon working fluid for reduced changes in specific volume, high energy density, positive saturated vapour line slope and an appropriate condensing temperature, expanded through a high-speed, fixed-nozzle, axial inflow turbine generator producing about 45 kW_e in a particular heavy-duty lorry application.

principle, the idea is attractive, offering the possibilities of solid-state cooling, heating and power generation from small, lightweight and potentially very reliable and rugged equipment. In addition, the waste power recovery is easily adaptable to varied form factors and thermal power influx (Bell, 2005). However, consideration has to be given to both the target ICE duty and to the way the electrical power could be usefully used, given that a 10% recovery would represent a greater amount of electrical power than is currently consumed by vehicles. Clearly, the envisioned powering of engine-driven accessories to electric drive is to the advantage of thermoelectric generation, as is the increasing hybridisation of vehicle propulsion (Yang, 2005). Although the thermoelectric device is itself small, the total package for producing the power is heavy and the target is to limit this increase to 50 kg. High-load and high-duty cycles are attractive, where the saving in fuel could help to pay for the economic cost of such devices, although consideration has to be given to the pumping loss caused by flowing exhaust gases through a heat exchanger and with the heat exchanger's pumping requirements. Generally, materials operating at 800–400 K are expected to dominate applications: many aspects have yet to be investigated, including material property and fatigue characterisation. In the near term, one method (Fairbanks, 2005) would be to use power-conditioning equipment (inverters) that would integrate with the 'beltless or more electric' engine concept or an integrated motor/alternator/starter. In the long term, should quantum dots fulfill their promise, there is the possibility that thermoelectric conversion could compete with the ICE itself. Although thermoelectric generation from exhaust heat is attractive in principle, materials with a higher conversion efficiency are desired and the heat exchange modules and electrical subsystems need to be designed. Finally, optimisation at a vehicle level needs careful consideration.

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