Dossier

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A Challenging Future for the IC Engine: New Technologies and the Control Role

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Abstract — *New regulations on pollutants and, specially, on CO_2 emissions could restrict the use of the internal combustion engine in automotive applications. This paper presents a review of different technologies under development for meeting such regulations, ranging from new combustion concepts to advanced boosting methods and after-treatment systems. Many of them need an accurate control of the operating conditions and, in many cases, they impose demanding requirements at a system integration level. In this framework, engine control disciplines will be key for the implementation and development of the next generation engines, taking profit of recent advancements in models, methods and sensors. According to authors' opinion, the internal combustion engine will still be the dominant technology in automotive applications for the next decades.*

Résumé — Un challenge pour le futur du moteur à combustion interne : nouvelles technologies et rôle du contrôle moteur — Les nouvelles normes sur les émissions, en particulier le CO_2, pourraient réduire l'utilisation du moteur à combustion interne pour les véhicules. Cet article présente une revue de différentes technologies en cours de développement afin de respecter ces normes, depuis de nouveaux concepts de combustion jusqu'à des systèmes avancés de suralimentation ou de post-traitement. La plupart de ces technologies demande un contrôle précis des conditions de fonctionnement et impose souvent de fortes contraintes lors de l'intégration des systèmes. Dans ce contexte et en profitant des dernières avancées dans les modèles, les méthodes et les capteurs, le contrôle moteur jouera un rôle clef dans la mise en œuvre et le développement de la prochaine génération de moteurs. De l'avis des auteurs, le moteur à combustion interne restera la technologie dominante pour les véhicules des prochaines décennies.

NOMENCLATURE

CAI	Controlled Auto Ignition
CAS	Crank-Angle Sloved
CI	Compression Ignited
DPF	Diesel Particulate Filters
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EV	Electrical Vehicules
GDP	Gross Domestic Product
GHG	Green House Gases
GPF	Gasoline Particulate Filters
HCCI	Homogeneous Charge Compression Ignition
HEV	Hybrid Electrical Vehicules
HIL	Hardware-In-the Loop
IC	Internal Combustion
I2V	Infrastructure-to-Vehicle
LNT	Lean NO_x Traps
LTC	Low Temperature Combustion
MIL	Model-In-the-Loop
MK	Modulated Kinetics
MVEM	Mean Value Engine Models
OBD	On-Board Diagnostics
ORC	Organic Rankine Cycles
PEMS	Portable Emissions Measurement Systems
PCCI	Premixed Charge Compression Ignition
PPCI	Partially Pre-mixed Charge Compression Ignition
RCCI	Reactivity Controlled Compression Ignition
RCP	Rapid-Controller Prototyping
SACI	Spark Assisted Compression Ignition
SCR	Selective Catalytic Reduction
SI	Spark Ignited
SIL	Software-In-the-Loop
VGT	Variable Geometry Turbines
VVT	Variable Valve Timing
V2V	Vehicle-to-Vehicle
YOLL	Years Of Life Lost

INTRODUCTION

Along the history, Internal Combustion (IC) engines have been and are the most spread technology in the automotive sector. Both compression and spark ignited engines have been used for more than a century for commercial and passenger cars, which have become a major factor in our culture and have transformed and organized social life: our mobility, urban planning, and consumption habits are structured at a high extent according to car requirements and the possibilities it offers [1, 2]. Cars are widespread in developed countries, approaching or even exceeding 0.5 cars per person in many of them [3, 4], and account for 84.1% of passenger displacements [3]. As shown in Figure 1, developing countries present a significantly lower car-person ratio. On the other hand, the economic growth in developing countries strongly correlates with the increase in the access to cars [5], and consequently there is a continuous increase in the size of the global car fleet. On rough numbers, transportation sector is responsible for about 40% of the world oil consumption, and in the next two decades 88% of the oil demand increase will be associated to the economic development of non-OCDE countries [6].

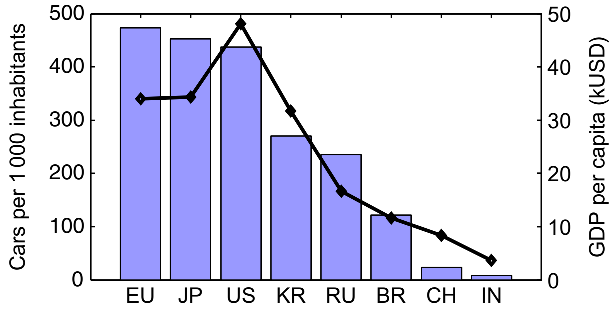

Figure 1

Cars per person (bars) and GDP per capita (line) in some selected countries. Source: the World Bank Open Data and Eurostat, 2009.

When analyzing the long term perspectives of the IC technology, oil dependence has been judged a major drawback related to the risk of crude reserves depletion. However, due to technology advancements in oil discovery and recovery, proved oil reserves to production ratio has held relatively constant at 40-43 years since the mid-1980s, while probable reserves to production ratio is greater than 130 years [7]. These figures could vary significantly with the increase of the global car fleet, but oil depletion is not the main reason today for technological evolution.

Beyond the crude depletion risk, the operation of the automotive IC engine is not free of negative impact. Transport accounted for about 26% of all energy-related CO_2 emissions in 2007 [8], and is a major source of pollutants affecting air quality. As a consequence of the development of the non-OCDE countries, a significant growth in the CO_2 production share is expected to 2050 [9], even in the case of strong cut off in global CO_2 production [10].

Nowadays, fossil fuel combustion technologies are under review due to the scientific community agreement on the impact of anthropogenic CO_2 emission on climate change [11]. Clear evidences on the climate change exist,

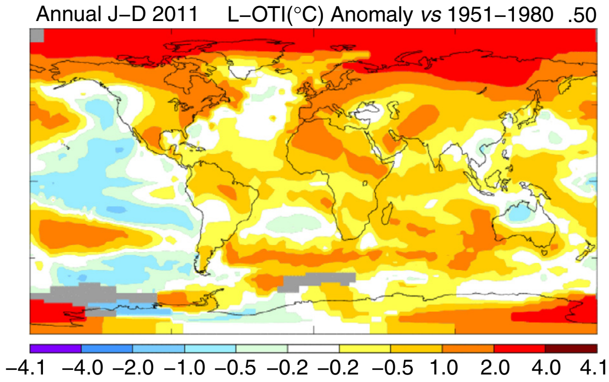

Figure 2

2011 annual mean surface temperature anomaly with respect to 1951-1980 period. Source: NASA Goddard Institute for Space Studies, using [12] method.

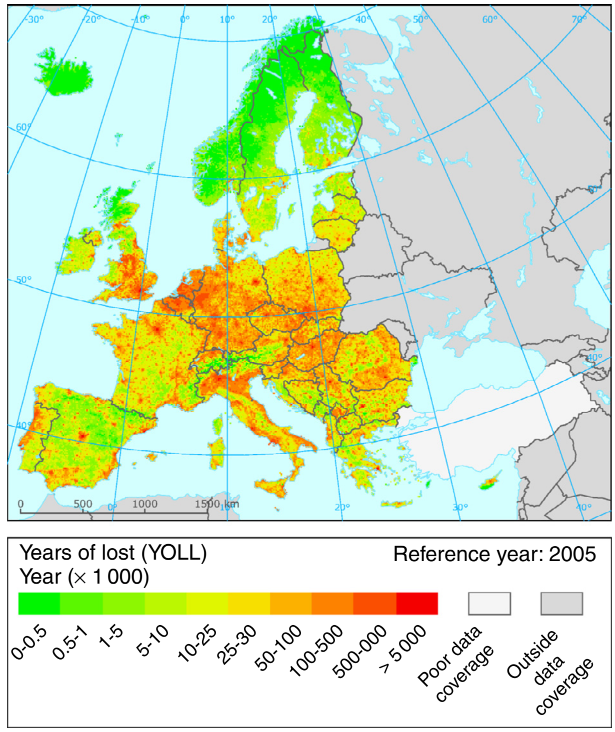

Figure 3

Years Of Life Lost (YOLL) in EEA countries due to PM2.5 pollution, data from 2005. Source: [14].

including indicators as vegetation changes, ice cores thickness reduction and sea level change, and also earth surface temperature, which has experienced a persistent growth along the XXth century. Mean global warming in 2011 was about 0.51°C with respect to 1951-1980 period although, as shown in Figure 2, significant geographic variation exist [12].

After some decades of political indecision, policies are being articulated in order to keep the global warming below 2°C. Consequently, long term objectives for world Green House Gases (GHG) emission have been set, with a reduction objective of 50% from 1990 levels to 2050 (which corresponds to objectives about 80%-95% for many developed countries [13]). As it will be reviewed later, a set of policies has been developed in many countries in order to control the impact of transport on CO_2 emissions.

Additionally, IC engines are responsible of other pollutants, as particulate matter, NO_x and HC. Although these pollutants are not considered as a global problem, they threaten plant and animal life in a local and regional scale. For example, Figure 3 illustrates the estimated years of life lost due to the exposition to PM2.5 in the EU countries according to [14].

Unlike CO_2, these sort of tailpipe emissions have been directly regulated for many years, and explicit limits must be fulfilled during the certification process. Emission limits have been lowered about 99% with respect to 1980 values, and persistent pressure is set for establishing even more stringent limits. Up to now, manufacturers have succeeded in developing emission control technologies for satisfying the regulation but in many cases emission control methods have a negative impact on engine efficiency, and then penalize climate change control [14]. The impact on CO_2 emission of some of the widespread techniques, as delayed combustion timing in IC engines for controlling NO_x formation, may prevent their application in a near future.

In this scenario, where clean and carbon free technologies are needed, the existence itself of the IC engine is under evaluation. This review paper does not present new results, but presents some of the latest advances on the IC engine technology and dicusses the future of the IC engine. Section 1 presents the general regulatory framework, the global market requirements, and the general perspectives of the IC engine. Section 2 reviews technologies under development, ranging from advanced combustion modes to boosting and gas recirculation technologies, and after-treatment systems. Finally, in Section 3 emphasis is laid on engine control, as a key technology for the implementation of advanced combustion techniques, and as the enabling tool at a system integration level and for the operation of multimode engines. In order to provide an updated view of the technologies and control problems under research, in many cases recent references have been favored with respect to pioneering works.

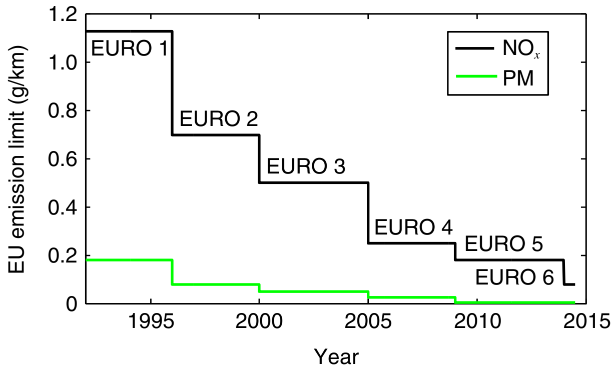

Figure 4

Evolution of the NO_x and PM emission limits for ligh duty diesel engines in Europe.

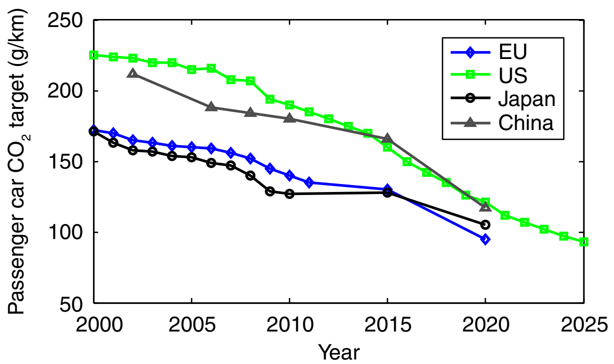

Figure 5

Comparison of CO_2 emission targets, expressed as g/km for the NDEC cycle; the series includes historical performance, enacted values for 2015 and proposed targets. Adapted from [16].

1 CONTEXT AND PERSPECTIVES

1.1 The Change in the Regulatory Framework

Recent years have experienced a change of paradigm in the regulatory framework. After two decades of tightening pollutants limits, nations are starting to implement GHG emission restrictions. If the limit of regulated emissions, as shown in Figure 4, has been persistently lowered, CO_2 emissions are being regulated for the first time. In addition to tax benefits for eco-friendly technologies, requirements on the fleet commercialized by manufacturers have been set [15]. Figure 5, adapted from [16], shows historical records and CO_2 emission target for cars in several world regions; for example, the 2020 target for CO_2 emissions in the EU is 95 g/km [15], equivalent to a 25% cut; other regions in the world present different (but also challenging) objectives. Local regulations are emerging and are expected to gain importance in the near future.

On the other hand, it is well known that the certification cycles for the different regions do not perfectly match the more complex situation of the real-life engine operation [17, 18], and in many cases manufacturers have tailored the emission control strategies for the homologation cycle. Thus, as reported in [19], it may happen that the reduction obtained in the type approval value does not necessarily translate in the same amount of reduction of real-life operation (this is valid for all the pollutants). Several initiatives are being set in order to mitigate this issue: emission assessment through independent research may be used for providing feedback to the regulation body; activities for developing and implementing harmonized cycles more representative of the real-world operation [20]; and also the proposal of using real-life evaluation. The latter includes the possibility of programming a random cycle from a set of real-life records, or using Portable Emissions Measurement Systems (PEMS) [21, 22]. Moving from the current certification procedure, with a known, defined cycle, to a statistical approach would pose difficulties to the current approach for engine calibration, and emission limits would be significantly stricter.

1.2 New Fuels

Next generation biofuels are expected to play a significant role in GHG abatement. According to [7], examples of default GHG reductions rate are 19% for palm oil biodiesel, 52% from sugar beet ethanol, and 83% from bio-waste biodiesel. Biofuel share increase may be a cost-effective solution for lowering the GHG impact of the automotive IC engines. According to [10], next generation biofuels combined with IC engines may provide a CO_2 cut similar of the development of electrical vehicles and renewable electricity generation share, but with a lower lifetime incremental cost of the vehicle.

Biofuel share is already significant in countries like Brasil, and many other countries are articulating laws for increasing biofuel share. As a consequence, future engines are expected to have an increased tolerance to variations in the fuel quality [23]. Such property will provide freedom to the user when refueling, and also will allow the engine manufacturer to cope with the regional differences in fuel quality. Different fuels may present non negligible variations in heating value, stoichiometric air-to-fuel ratio, and reactivity, thus influencing engine performance and emissions [23, 24]. Dealing with excessive sulfur content, which poisons after-treatment catalysts, is significantly challenging, as it may be the operation of different advanced combustion concepts with an uncontrolled fuel reactivity.

1.3 IC Engine Perspectives

In the presented framework, with an increasing pressure on CO_2 emission reduction and the necessity of clean technologies, the IC engine future is on debate. As a consequence, different powertrain solutions are being evaluated, as Electrical Vehicles (EV) and Hybrid Electrical Vehicles (HEV).

Media has paid lot of attention to EV, which are sometimes presented as the only way of reaching the CO_2 targets. Although in terms of tailpipe emissions during operation IC engine is easily beaten by the EV, the EV advantage in CO_2 and emission footprint depends on the electricity production mix. This aspect must be carefully considered: according to [9] coal will still be the primary source for electricity generation in 2035. Hence, EV implantation will have no direct benefit in the mid-term, and it can even increase the emission in terms of particulate matter depending on the national electricity production mix. Additionally, if non-conventional fuels and life-cycle emission are considered, IC engines can still compete against EV [10].

EV market share did not reach 0.01% in the EU in 2012 [25]. On the other hand, HEV, available in the market from 1997, represent today a 16% share in Japan [25]. However, the penetration of the hybrid technology in other markets is uneven, and its share in the US in 2011 was 4% [26], while in the EU did not reached 1% in 2012 [25]. According to the ACEA [27], most stakeholders assume a realistic market share for new, electrically chargeable vehicles in the range of 3 to 10% by 2020 to 2025.

Therefore, even in the worst case scenario, IC engines will be then still available for several decades. Furthermore, they are constitutive parts of some of the alternatives (as HEV), and may act as enablers for others, as in the case of their application as range extenders for plug-in hybrids (PHEV).

According to [28], the technologies for reaching the 2020 target (average fleet CO_2 emission of 95 g/km) with IC engines are already in the market; however, technological evolution is needed in order to meet future requirements in the legislation. The improvement in the powertrain efficiency (and mainly in the engine operation) is the major area for reducing light duty vehicles CO_2 footprint, while aerodynamics and tire technology improvements will also contribute significantly for heavy duty vehicles. The cost for reaching 2020 CO_2 targets with pure IC engine technology is estimated in 1 000 Euro per car. This cost is similar to the cost associated to the control of the regulated emissions [29], but in this case the consumer is benefited by the fuel saving, and the payback will be of 3 years [28]. Going beyond 70-80 g/km will require the extension of hybrid electric technology or significant lightweighting.

Lightweighting combines the application of improved design techniques with lighter materials, as high strength steel, aluminium, magnesium and polymer composites. Although extreme lightweighting may negatively impact vehicle cost [30], fuel saving and lower power requirements can make it cost-effective for around 6 USD per kg of mass reduction in the case of EV, and up to 12 USD/kg for IC powered vehicles [31].

2 TECHNOLOGIES FOR THE FUTURE IC ENGINE

Although predicting the technological evolution of the automotive market presents difficulties, it must be considered that most changes in the automotive field are progressive. According to Figure 6, where historical market penetration rates of different technologies in the US [26] are depicted, it has often taken more than a decade for a new technology to attain an industry-wide car production fraction of 20 to 60% after the first significant use, and five to ten years more to reach maximum market penetration. Only regulatory-driven technologies attain a significant market share in less than a decade [32], as it has happened in the past with Diesel Particulate Filters (DPF) for light duty vehicles, and Selective Catalyst Reduction (SCR) and DPF for heavy duty vehicles.

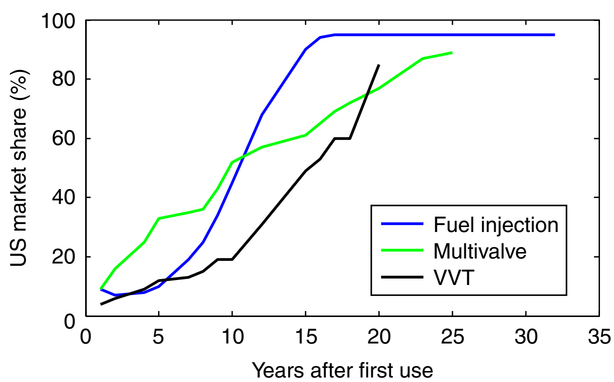

Figure 6

Penetration rate of several technologies after first commercial usage. Adapted from [26].

The review is centered in 4-stroke engines, which are today regular solution for passenger cars and commercial vehicles. Anyway, most of the reviewed technologies may be indistinctly applied to lighter 2-stroke engines, which today are restricted in automotive applications to small mopeds. Cyclic revision of the 2-stroke technology for light and heavy duty applications exists [33-35], and new market niches could be specially suited for them (*e.g.* range extenders).

2.1 New Combustion Concepts

For many years IC engine combustion concepts were monopolized by two radically opposite concepts: Spark Ignited (SI), and Compression Ignited (CI) combustions. The former uses a nearly-stoichiometric premixed charge of air and a low-reactivity fuel, and the combustion is triggered by an electrical spark, which allows an accurate control of the combustion phasing. The latter injects a high-reactivity fuel in a previously compressed inert cylinder charge, resulting in a diffusion flame with a low global equivalence ratio. If SI combustion is characterized by a flame front in an homogeneous mix and the use of high octane fuels (gasoline, natural gas, liquefied petroleum gas, alcohols, etc.), CI combustion concept relies in a non-homogeneous diffusion flame, and requires a fuel with a high tendency to auto-ignition (Diesel, oil, esters, etc.).

A tight control of the air-to-fuel ratio and the use of three-way catalysts have been the spread solution for mitigating the HC, CO and NO_x production associated with the SI combustion concept. Hence a significant research effort was centered during the last decades on fuel dosing (from old carburetors to multi-port injection, with closed loop lambda control). Nevertheless, main disadvantage of SI combustion is related with the risk of auto-ignition of the mix, also known as knock, which limits the cylinder compression ratio and the spark advance; and also the need of throttling the intake flow in order to control the engine load. Both aspects impact the engine efficiency, which is significantly lower than those of the CI engines.

On the other hand, classical CI combustion permits a high efficiency engine operation, but suffers from NO_x and soot production due to the high local equivalence ratio and temperature in the flame. In addition, noise becomes a major issue due to the fast combustion in the initial (*i.e.* premixed) period of the combustion. Although the use of delayed combustions and high Exhaust Gas Recirculation (EGR) ratios permit mitigating the pollutant formation, this cannot be done at no cost, and it penalizes engine efficiency. Multi-injection concepts (pilot injection and post injection) have been also used for mitigating combustion noise and lowering soot emission, but again with an impact on the engine fuel efficiency.

Nowadays the situation is far more complex and many combustion concepts are under research, with different perspectives of implantation. Significantly, gasoline and Diesel fuels are no longer exclusively associated with SI and CI respectively, nor homogeneous mix and non-homogeneous, or stoichiometric and lean. Providing a complete review of all the combustion concepts exceeds the scope of this paper, but a rough classification may be done:

Spark ignited concepts. In opposition to traditional (near) stoichiometric homogeneous SI engines, the following combustion concepts with significant fuel-saving potential are being developed:

– lean-burn combustion. In this case, an homogeneous mix is used but, in opposition to conventional SI concept, a low fuel-to-air ratio is used, which provides advantages in terms of fuel efficiency (because of reduced throttling at part load, and of lower heat losses to cylinder walls). In addition to problems associated to misfiring and cyclic dispersion, this combustion concept complicates the after-treatment since conventional three way catalysts are not able to reduce NO_x with excess oxygen;
– stratified gasoline combustion. Lean-burn combustion is limited by the inflammability of the mix; in order to operate the engine with a lower global fuel-to-air ratio, it is necessary to stratify the cylinder charge. This can be done with the high-pressure in-cylinder injection of the fuel, which prepares a near stoichiometric mix in the immediacy of the spark plug, while the rest of the cylinder is filled with fresh air. State-of-the-art technology is referred to as spray-guided, and multi-pulse strategies may be used for reducing spray penetration and for improving the homogeneity of the fuel-air mixture in the area of the spark plug gap [36].

Compression ignited concepts. New CI concepts are based on the self-ignition of premixed lean mixtures, usually highly diluted with EGR [37]. This results in a Low Temperature Combustion (LTC), which is characterized by its low NO_x production. If the combustion speed is high enough, efficiency is also improved with regards to a classical CI engine. This concept has been applied using early and late injections, with Diesel and gasoline. When the injection is performed during the intake stroke for ensuring an homogeneous mixture, combustion is referred as Homogeneous Charge Compression Ignition (HCCI) or Controlled Auto Ignition (CAI), for Diesel and gasoline respectively. If the injection is performed during the compression (but before the usual range for CI engines), the combustion concept is usually referred to as Premixed Charge Compression Ignition (PCCI) or as Partially Pre-mixed Charge compression Ignition (PPCI), depending on the ignition delay. Although late injection has also been used, like in Modulated Kinetics (MK) concept, it worsens fuel efficiency. Potential efficiency of PCCI and PPCI exceeds 50%, but there are still significant problems to be addressed before the market implementation, as combustion phasing and the extension to the full engine range.

Combustion phasing is complex because, alike in conventional SI and CI engines, there is no event triggering the combustion (*i.e.* spark or the injection near the top dead center). Many variables, as EGR rate, cylinder temperature and fuel characteristics, affect the auto-ignition delay, and significant cyclic dispersion may occur. Furthermore, instability may occur because one cycle affects the temperature of the subsequent cycle [20].

Several proposals try to provide a direct way of controlling the combustion phasing: a primary gasoline injection for creating the premixed charge may be combined with a secondary Diesel injection for controlling the combustion timing, in the so-called fuel Reactivity Controlled Compression Ignition (RCCI) [58]; on the other hand, Spark Assisted Compression Ignition (SACI) concept uses an spark ignited flame propagation for triggering the auto-ignition.

One significant issue of next generation engines is the possibility of shifting between combustion modes: the same injection and combustion hardware may be used in different combustion modes (for example from homogeneous to stratified, or from PCCI to conventional CI).

Also the possibility of combining different kinds of fuel is under study. This can be done with two different, and almost opposite, purposes: for adapting the fuel reactivity to the combustion specifications (as in the case of RCCI), or for adapting the combustion settings, and even the combustion mode, to the fuel properties. The latter may play a significant role for coping with regional variations in fuel quality or with market availability, extending the functionality of today's dual-fuel and multi-fuel engines already in the market.

In parallel with the advancements in the combustion concepts, injection systems are also experiencing a significant development, since the use of multiple-injection spray-guided mix formation concepts imposes demanding requirements. General trends include the increase of injection pressure (with short term objectives beyond 3 000 bar for Diesel and 1 000 bar for gasoline), optimized nozzle-hole geometries and direct needle lift control, which will make possible injecting very low quantities and performing injection rate shaping. In a future scenario with a wide variety of marketed fuels, it must be considered that spray characteristics are affected by fuel properties [87], and that significant compatibility problems could appear with the injection hardware.

2.2 Boosting Technologies

For many years standard solution had been using atmospheric SI engines and turbocharged CI engines. For the latter, in order to (partially) solve the coupling problem between the IC engine and the turbocharger, waste-gate and Variable Geometry Turbines (VGT) have been widely used. Engine downsizing is a widespread trend in current automotive engines: CI engines have continuously increased their rated power over the last 15 years on the basis of a continuous increase in the boost pressure and the improvement of the fuel injection technology. In the case of SI engines, turbocharged engines - for many years restricted to sportive applications - are extending their share, and the SI engine is also experiencing a similar trend to that experienced in recent years by the CI engine.

Alternative boosting technologies are being explored in order to decrease turbo-lag and to broaden turbocharger operation range, limited by surge and overspeed. A good review of recent advancements and alternatives in Diesel engine boosting technologies may be found in [106], whose conclusions are summarized in Table 1. There different technologies are compared with the current VGT technology in terms of engine low end torque, dynamical response, engine power, operation range, fuel efficiency, packaging, complexity of the system, high pressure EGR capacity, effect on the temperature at the catalyst and technology availability. Some of the possibilities included in Table 1 are already present in the market, although none of them with a significant share.

In many cases, new boosting methods rely in the combination of existing technologies, as the combination in parallel or series of several chargers, either mechanical or turbochargers. Also electrical or mechanical assistance is being explored for improving the system response time. The use of sequential or multi-mode systems needs an accurate mode transition control for preventing disturbing the driveability during the transition [37].

Finally, it must be highlighted that downsizing trend is pushing turbocharging to its limit: on the one hand, the high compression ratio required is causing thermal problems at the compressor and intake system (this may be mitigated in series systems with intermediate cooling), while on the other hand, especially for the case when low engine power is required (*e.g.* for range-extender applications), available turbocompressors in the market are way too large for the application.

TABLE 1

Potential of the main boosting architectures with regards to a VGT system, adapted from [41]. TC: turbocompressor, SC: supercharger, TCD: turbocompounding

Technologies	Low-end torque	Delay	Maximum power	Range	Fuel economy	Packaging	Complexity	HPEGR capabilities	Temperature at catalyst	Technical availability
Sequential parallel two-stage TC	+ +	+ +	o	+ +	-	-	- -	+	o	+ +
Serial two-stage TC	+	+	+ +	+	+	- -	-	+ +	- -	+ +
Sequential serial two-stage TC	+ +	+ +	+	+ +	+	- -	-	+	-	+ +
Single stage mechanical SC	+ +	+ +	o	o	- -	-	o	- -	+ +	+ +
Mechanical auxiliary SC	+ +	+ +	+	+ +	-	- -	-	o	o	+ +
Electrically assisted TC	o	+	o	o	o	o	- -	+	o	- -
Electric booster + TC	+ +	+ +	+	+ +	+	-	-	o	o	-
TC enhancement devices	+	+	o	+	o	o	-	o	o	-
Mechanical TCD	o	-	+	o	+ +	- -	-	+	-	+ +
Electrical TCD	o	-	+	o	+ +	- -	- -	+	-	- -

2.3 Charge Composition and Temperature Control

New combustion concepts need an accurate control of the charge composition, which has been traditionally ensured through high-pressure EGR in CI engines, and internal EGR in SI engines. However, the need of increasing the EGR rate, improving its homogeneity, and controlling its temperature, has boosted the development of low pressure EGR loops and water cooled intercoolers. Although low pressure EGR is not a new technical solution [43], it has been traditionally discarded because compressor wheel damaging and soiling and acid corrosion problems in the intercooler [44]. Recently, new engine technologies, like particulate filters for exhaust gas after-treatment [45], the development of high resistance intercoolers [46] and the generalization of low sulfur content fuels, allow using low pressure EGR systems.

New architectures may combine different EGR systems (high pressure, low pressure, and internal EGR) which are operated in order to provide a tight control of the in-cylinder composition.

2.4 Full-Flexible Variable Valve Timing

Variable Valve Timing (VVT) technologies are widespread in SI engines; according to [26] 94% of the light duty models marketed in the US in 2011 were equipped with different technical solutions that allowed varying the valve timing and/or the valve lift.

However, full flexible continuous valve timing systems are still in an early development phase. Although camless systems are not still in production, engines using electro-hydraulic systems have been already marketed [47] and provide a high flexibility of the valve timing with a cycle-to-cycle response time.

Some of the advantages of such full flexible VVT systems are the control of the engine charge without intake manifold throttling, effective compression ratio control, or the application of alternative engine cycles as Miller and Atkinson concepts through the modification of the compression and intake stroke. Cylinder deactivation for mechanical losses abatement and the possibility of switching between 2-stroke and 4-stroke operation are also possible [48]. Finally, they may also serve for the cycle-to-cycle control of the cylinder charge.

2.5 After-Treatment

The development of after-treatment systems has been a major topic of research for several decades, and this field is still considered a key player for the next generation IC engines. A detailed revision of latest advancements may be found in [32]. Technologies in an early stage of implantation are Lean NO_x Traps (LNT) and Selective Catalytic Reduction (SCR) systems, and significant advances are expected in after-treatment systems at the integration and manufacturing levels. Finally, Gasoline Particulate Filters (GPF) are at an early stage of development.

In general, after-treatment systems penalize fuel consumption because of added pressure losses and of regeneration strategies to be implemented. However, they may impose a lower fuel penalty than other strategies for controlling the raw pollutant production. Today, there is no general consensus about the cost-effective solution for NO_x control in lean conditions (*i.e.* CI and lean SI engines). Although in the past EGR and NO_x-optimized combustion was sufficient, nowadays it is assumed that SCR or LNT will be necessary for NO_x reduction in lean operation.

In the case of LNT, the NO_x reduction agents are HC and CO purposely produced in the combustion during the periodic regeneration events. For that the engine operation must be switched from lean to rich conditions, which imposes fuel penalty [49]. Periodic desulphation processes may also be needed.

SCR systems need the dosage of an ammonia source (typically urea) and there is a trade-off between the raw emission control using delayed injection timing and high EGR rate, and the after-treatment control consuming urea [50].

2.6 Mechanical Losses Abatement

Improving engine mechanical efficiency has a direct impact on fuel saving. Downsizing (using high boost pressure for shifting the operation of the engine to higher loads) has been the dominant trend in engine design in recent years, and provides a direct improvement in the mechanical efficiency of the engine. At the same time, downspeeding also has a significant fuel saving potential due to the reduction of the friction power [51], while cylinder deactivation techniques may be used for saving the pumping work when operating at low engine load. Finally, significant advancements have been also achieved in friction optimized design, and the use of light-weight materials and low-friction surface finishing.

Concerning auxiliary equipment, active systems are progressively substituting passive components. This allows to modify their power consumption, and even disconnect the system according to the operative conditions. Stop-start of the engine for avoiding idling is expected to be a widespread technology in a near future, and paves the way to mild hybrid electric system.

2.7 Thermal Management and Waste Heat Recovery

Paradoxically, although being one of the main loss flows in the IC engine, heat has become a precious resource during engine operation, and specific actions are to be implemented during warm-up phase, or when extra heat flow is required for after-treatment regeneration. In this sense, stop-start adds additional complexity from the thermal management point of view.

In the case of the thermal optimization, and because of the temperature drop inherent to the heat transfer phenomenon, a holistic approach is needed at a powertrain level: heat must flow from high temperature elements to those needing a lower temperature. Electrical heated systems may add an extra degree of freedom and may be used for accelerating the light-off of different after-treatment devices [52].

Waste heat recovery is also under research, considering several technologies for electrical or mechanical energy generation:

- mechanical turbocompounding, where the internal combustion engine is equipped with an additional power turbine [53, 54]. The power turbine is placed in the exhaust line and is mechanically coupled to the engine crankshaft via a gear train;
- electrical turbocompounding, which consists of an electric motor/generator coupled to a turbocharger [55, 56]. The generator extracts surplus power from the turbine, and the electricity produced is used to run a motor assembled/fitted to the engine crankshaft;
- thermoelectric materials installed in the exhaust pipe, thus providing at least some of the powertrain electric power requirements [57, 58];
- Rankine cycle, where the steam is generated from the thermal energy in the exhaust gases. Particularly, Organic Rankine Cycles (ORC), based on the use of organic fluids, are especially suited to recover energy from exhaust gases at low temperatures.

The ORC technique has a lower impact on pumping losses than turbocompounding. On the other hand, ORC shows higher efficiencies than thermoelectric materials for the recovery of residual thermal energy [54, 59]. Several studies have examined Rankine cycles for exhaust gas heat recovery in vehicle applications [60-63].

3 THE CONTROL ROLE

Precedent section has shown the wide variety of technologies that are under review. Although it is impossible to venture the winning technology, what can be clearly stated is the growing importance of the engine control for today and future IC engines. This is based on the importance of this domain both as technology-enabler, and at a system-integration level.

Many of the technologies presented in the precedent section need an accurate control for being implemented. In some cases, this is due to the high sensitivity of the process itself, while in other cases is because accurate transition between operation modes is needed. Some of the hot topics of research are reviewed next.

3.1 Combustion Control

A good example of the crucial importance of the control is the new LTC concepts, where the combustion is initiated due to the self-ignition of the mix as a result of a chemical kinetic process. Characteristic times are significantly affected by temperature, gas composition and fuel quality, and slight variations in these quantities may lead to huge variations in the combustion timing. In some cases, because of the variation of the temperature in the residual gas fraction, the system may become unstable. In order to control the combustion phasing, fast actuation systems, as injection settings and VVT, are cycle-to-cycle adapted for controlling the combustion [64, 65]. In most cases it is done on the basis of an in-cylinder pressure measurement, although several alternatives have been also proposed [66].

In-cylinder pressure has been used in research from the very beginning of the IC engine for diagnosis, and many applications have been proposed for conventional SI and CI engines (*e.g.* for misfire detection [67], for in-cylinder trapped air mass estimation [22, 68, 69], etc.); however, it has not been implemented until recently to series production. New piezo-resistive sensors [70, 71] may be a cost-effective alternative to traditional piezo-electric sensors.

Another important issue concerns the inability of LTC concepts of operating in the complete engine range. For shortcutting this problem a mode switching to another combustion mode may be used. For example, [72] uses the conventional CI combustion for idling and full load, while [73] deals the transition from LTC to SI for cold start, idle and medium to high loads. In all cases, it is a challenging situation because of the huge differences in the required charge composition and because combustion instabilities, misfiring or significant torque disturbances can compromise driveability. VVT, combined with gas exchange models [64], may be the key technology for providing a cycle-to-cycle control of the charge composition.

Other active field of research in lean SI engines and CI engines is air-to-fuel ratio control, while closed loop CI combustion control is also being researched. The availability of new production sensors, and the possibility of performing intra-cycle control [74] may be used for significantly reducing the deviations between cycles and cylinders.

Finally, also multifuel concepts are gaining attention from the scientific community. Efforts are being made for developing fuel composition sensors able to operate with a wide range of fuels (including gasoline, Diesel and other alternative fuels). For example, light transmission in the infrared spectrum [75] or electrical capacitance [76] measurement may be used for quantifying several relevant fuel quantities and inferring fuel composition. As far as fuel reactivity may be determined, such sensors may play a major role for the implantation of new combustion technologies, even avoiding close loop combustion control. Another significant benefit of these sensors is the possibility of adapting the engine calibration to the fuel properties, since as stated in Section 1, fuel quality may significantly vary due to regional fuel specifications, and also because several alternative fuels may be present in the market.

3.2 Air-Path Control

For more than 2 decades, EGR-VGT coordinated control has raised the interest of researchers in the academia and the industry, because the response of the system is highly non-linear and presents properties as gain inversions and non-minimal phase behavior.

In recent years, air-path system has increased in complexity due to the development of low pressure EGR systems, and the deployment of different sequential turbocharging systems. Degrees of freedom in the system actuation have experienced a significant growth: in addition to EGR valves, throttle, and waste-gate or variable nozzle turbines, new systems also integrate intercoolers by-passing valves, and different active and passive valves for switching between operation modes.

System modeling for the air-path is quite well developed, and model-based control has been implemented to a high extent. Although gas pressure, air mass flow and concentration sensors are widespread, observers and system models are widely used, and sometimes used as feedback quantities, [77]. In fact, one of the main difficulties resides in selecting the cost-effective sensor combination for controlling the system, while satisfying the robustness requirements [78]. In this sense, it must be considered that slight cylinder-to-cylinder dispersions that were no critical in conventional CI engines, may become a major problem when LTC is considered. Joint control of air and fuel path is also in research [79], taking into consideration the close interaction between the two systems.

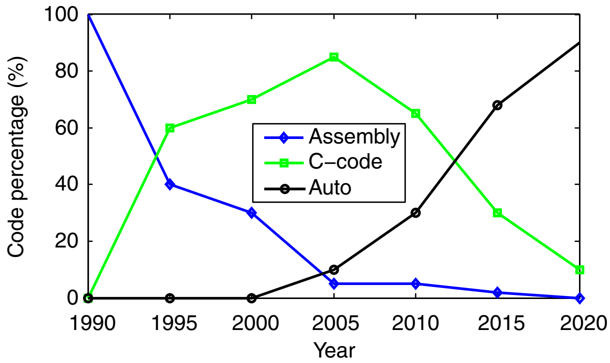

Figure 7

Evolution of the language used for ECU programming. Adapted from [89].

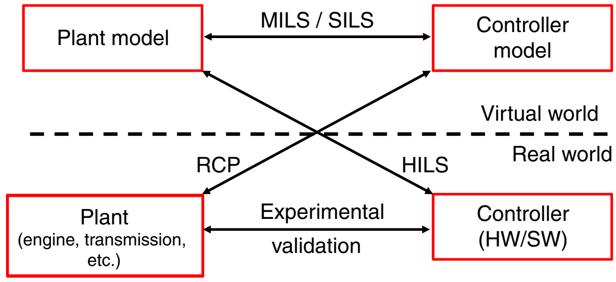

Figure 8

Different combinations of real and virtual components according to a model-based development technology perspective. Adapted from [90].

In the case of multi-mode systems, high-level control is needed for deciding the mode transition, which must ensure a smooth variation of the boost pressure and charge composition for avoiding impact on torque or other sensitive quantities. Main challenges are related to the necessity of accelerating turbochargers to working conditions, of transferring the control authority between different systems, and of protecting the different machines against surge and overspeed. In some cases coordinated control of the fuel injection for compensating torque disturbances may be needed [42].

3.3 After-Treatment System Control and Diagnosis

Even in the case of passive systems, as Diesel oxidation catalysts or three way catalysts, an accurate control is needed in order to ensure that operation conditions are reached and maintained. Beyond air-to-fuel ratio control, current IC engines implement thermal management techniques in order to accelerate catalyst light-off during cold starting.

Even more challenging is the situation of systems as DPF and LNT, which need a periodic regeneration. This imposes requirements in the gas temperature and composition, that may need significant variations in the combustion and air-path settings. In some cases, a switch in the combustion or boosting mode may be necessary. Lot of research effort is done in modeling the raw pollutant production [80, 81] and the regeneration process itself [82] and in the limit, model-based approaches may be used [83].

In recent years, SCR control has received significant attention; in this case optimal urea dosing stands the major difficulty. Not only the trade-off between NH_3 slip and NO_x conversion must be considered, but also the urea consumption must be kept controlled for avoiding unscheduled refilling. Closed-loop control is needed for fulfilling the regulation and diagnosis [84], and NO_x sensors [85, 86] are already in production. SCR systems may be controlled despite the existence of several chemical species in the exhaust and the cross sensitivity of NO_x sensors to NH_3 slip [87, 88].

Although virtual pollutants sensors (*i.e.* models) may be used for control purposes, after-treatment system diagnostics need of sensors. In addition to binary and linear lambda sensors and the already cited NO_x sensors, resistive sensors for particulate matter are being developed [71].

3.4 System Integration

From a system-integration level, engines are becoming increasingly complex multi-agent plants. Cross effects and the existence of several operation modes, which may be triggered from a subsystem level, complicate the design of the control structure and its calibration. Identifying the interactions, limits and requirements from the subsystem level is a must for the control system development, and a key point for shortening research-to-market time.

In the last decade, significant advances have been done in terms of standardization of the control software. Multilayer design and the use of re-usable component oriented functions allow to easily modify the control system when new elements, as sensors or actuators, or new systems are added or changed. In this sense, as shown in Figure 7, high level languages and automated code generation are replacing low-level implementations [89].

Model-based development techniques are now widespread in the ECU and engine development process. Figure 8 presents some of the usual techniques in the development process, including Software-In-the-Loop (SIL), Model-In-the-Loop (MIL), Rapid-Controller Prototyping (RCP) and Hardware-In-the-Loop (HIL), which provide different approaches for component and control system development and validation [90].

Preferred approach for component modeling varies depending on the purpose of the model, and a wide variety of modeling concepts exists from simple data driven models, to complex three-dimensional physical based models [91] . In general, Mean Value Engine Models (MVEM), derived from simple mass and energy balances, are considered sufficient for air-path modeling, while in some cases Crank-Angle Solved (CAS) models are combined with MVEM for the combustion modeling.

One of the main problems of the current ECU code is the significant calibration burden. The complexity of the problem is rooted on the high number of degrees of freedom associated with the electronically controlled systems. As a consequence, the number of parameters to be tuned is continuously increasing. The existence of several modes (triggered by temperature, after-treatment regeneration, etc.) adds additional complexity to the system. Since most requirements at a subsystem level are not propagated to the high level control but fulfilled through calibration, current control systems usually result in a huge collection of tables. Current ECU have several tens of thousands of tunable parameters, which are tuned by some more or less smart trial-and-error approach, involving a test-intensive process. Beyond the time-consuming process, the resulting system lacks of any optimality, and has limited robustness and adaptability.

Model-based calibration, where the modeling environment is also used for developing an initial calibration, can alleviate the experimental work. Model-based approaches are also used for control system verification and validation [92], and for developing and tuning OBD strategies [93].

Developing a systematic approach for deriving the control system from a pre-existent system model, able to integrate subsystem requirements, would be a great advancement. In the limit, optimal control techniques may be used on the basis of existent engine models. Many attempts exist in the literature but, in general, they are fractional and subsystem oriented (*i.e.* they are centered in low level control of a given subsystem, usually tracking a reference, rather than the engine operation global optimization). Some recent examples may be found in [65, 94-97].

According to [98], main difficulty here is the lack of sufficiently precise models for design and operation, and of tools for on-line identification. One significant problem is that a model may work accurately at a subsystem level, but when coupled with other models, significant deviations may occur because of several closed-loop interactions at an engine level [97]. Furthermore, many models are too simple for catching the actual complexity of the system and their prediction capabilities are limited to the identification dataset; this is specially significant in combustion and pollutant formation models [80, 96].

The high variability in the engine condition and operation is another challenging problem. Unit-to-unit manufacturing discrepancies, ageing and the existence of an infinite combination of use cases, create a complex situation that is usually solved through the search of robust solutions. Although control systems are to a high extent static in their conception, adaptive capabilities are being progressively included [99] at a subsystem level (*e.g.* for injector drift compensation or idle control), and are judged to play a significant role for multi-fuel engines. Additionally, the availability of environmental information, through geo-localization, Infrastructure-to-Vehicle (I2V) or Vehicle-to-Vehicle (V2V) networks [100, 101], as the prediction of the driver behavior [64, 102], could be used in a near future for optimizing the engine management according to the use conditions.

Such extra information provides several paths for optimizing the engine operation, from fuel and emission optimised driving assistance [103-105] to constrained look-ahead control [106], platooning and cooperative driving [107-110]. In addition, engine control system calibration may be adapted to the varying conditions and local restrictions over emissions [111]. All these techniques may play a significant role, even with the standard combustion modes, if the certification procedures are based on real-life evaluation instead of homologation cycles known *a priori*.

Finally, the application of IC engines in electrified powertrains (as HEV or as range extenders for EV) supposes a specific application where frequent stop-start will impose severe conditions from the thermal point of view, which may have critical effects on after-treatment devices and combustion performance. Powertrain high-level management may consider the cost associated with the IC engine cold-start and the off-design operation of the after-treatment systems, and apply advanced model-based thermal management techniques in order to satisfy the thermal restrictions. One significant advantage of the hybrid powerplants is their ability of decoupling the IC engine torque from the user torque requests [112]. That provides an extra degree of freedom that may be profited for the controlled regeneration of after-treatment systems, and for smoothing IC engine transients [113].

CONCLUSIONS

The paper has reviewed the mid-terms requirements that the IC engine must satisfy. On one hand, legislation is becoming more stringent in terms of pollutants and CO_2, while on the other hand globalization, reduced time to market and the variability of fuel quality will change the global scenario. Despite these threats, according to authors' opinion, IC engine will maintain a key role in the next decades, although significant technological evolution is expected for improving the engine efficiency.

Technologies already ready for the market include stop-start, some advanced boosting concepts and different EGR and VVT systems. Significant advancements in the after-treatment systems have been already implemented to deal with lean combustion. In a mid-term horizon many other technologies could emerge, as low temperature combustion concepts, or modifications in the operation cycle. Since it is not possible to known which will be the winning technology, current situation presents a technological over-diversification, with a huge research and economic effort associated with the wide variety of technologies and combinations.

Engine control is an enabling tool at a subsystem level, since many of the advanced concepts need an accurate control for their operation, but especially at a system integration level. The existence of multiple operation modes, and the close interaction between the different subsystems need a holistic approach and the use of a high-level control. Managing subsystem requirements, operation limits and their interaction, providing a systematic calibration procedure and adapting the control system to variations in the environment and to engine ageing, are some of the active fields of research.

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