

Technology Comparison for Spark Ignition Engines of New Generation

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ABSTRACT

New gasoline engine design is highly influenced by CO₂ and emission limits defined by legislations, the demand for real conditions fuel economy, higher torque, higher specific power and lower cost. To reach the requirements coming from the end-users and legislations, especially for SI engines, several technologies are available, such as downsizing, including turbocharging in combination with direct injection. These technologies allow to solve the main issues of gasoline engines in terms of efficiency and performance which are knocking, part-load losses, and thermal stress at high power conditions. Moreover, other possibilities are under evaluation to allow further steps of enhancement for the even more challenging requirements. However, the benefits and costs given by the mix of these technologies must be accurately evaluated by means of objective tools and procedures in order to choose among the best alternatives. This work presents a comparison at concept level between the main technologies that are currently being developed, considering not only the technical benefits, but also their cost-effectiveness. The analysis is carried out on the basis of studies from the technical literature, integrating missing data by means of evaluations performed with engine-vehicle simplified models, considering the most important powertrain architectures.

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INTRODUCTION

Figure 1 shows the macro-trends that are shaping the future of the automotive industry. Some of them have a considerable impact on the vehicle propulsion system. The most significant ones are:

- sustainability, namely the simultaneous reduction of CO₂/ fuel consumption and emissions;
- autonomous driving;
- powertrain electrification.

In this scenario, as shown in Figure 2, internal combustion engines will still have a key role, as confirmed by many studies [3,2].

In long-term scenarios, it is still assumed the presence of a thermal unit in most powertrain configurations, albeit with varying degrees of electrification. The pure electric propulsion can mitigate the problem of the cost of fuel, as shown in [5,6,7], and the local emission of

vehicles, even though it does not seem to solve the problem of fine dust, mainly due to asphalt wear, tires and brakes, and as such directly linked to the weight of the vehicle, as shown in [12].

In purely electric vehicles, it is necessary to replace functions that are not closely related to propulsion, which are carried out by the thermal unit, as described in Figure 3, namely:

- production of electricity for devices on board the vehicle;
- mechanical energy production for the air conditioning system [8,9,10];
- production of thermal energy to heat the passenger compartment.

In the absence of an internal combustion engine that converts chemical energy stored in the fuel, the additional functions [9,10] require an electrical energy storage on board possibly much larger than what is necessary for traction only, with negative impacts on cost, weight, range and charging times.

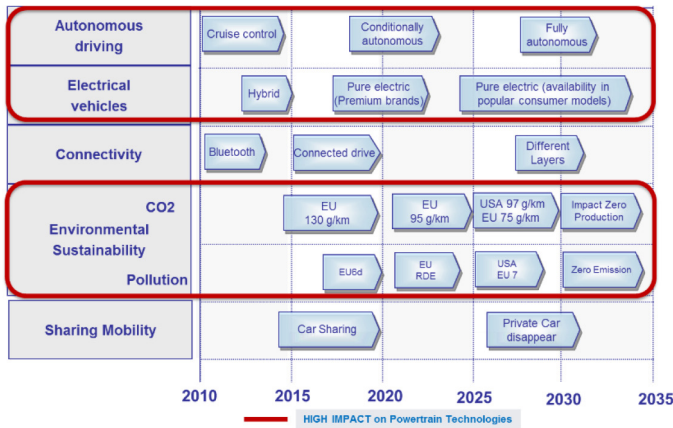


Figure 1. Automotive Technology Trends

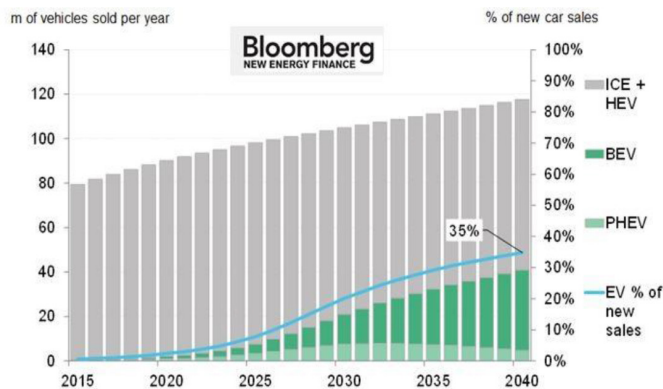


Figure 2. Powertrain market scenario, Bloomberg 2016

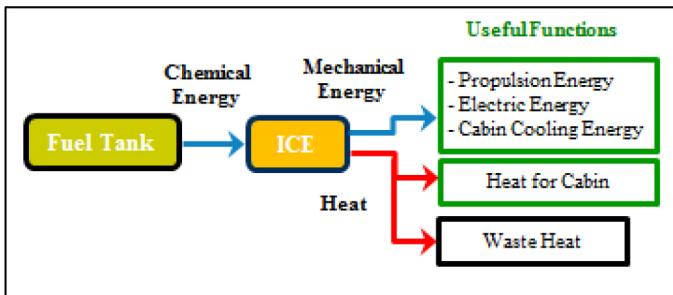


Figure 3. Energy flow and functions in ICE based vehicle

The effectiveness of a purely electric powertrain for the global reduction of CO₂ is another item that poses some doubts. Indeed, the most correct way to evaluate the environmental impact is to consider the so-called Well-to-Wheel (WTW) [13,14,15] efficiency, which is the product between the production yield from the primary source and distribution of the fuel (or energy carrier), said Well-to-Tank (WTT) and the conversion efficiency of the fuel/ energy carrier into energy for propulsion, said Tank-To-Wheel (TTW):

$$WTW = WTT \times TTW \quad (1)$$

Considering this approach, the effectiveness of the pure electric propulsion becomes significant when the energy production comes mainly from renewable sources [14]. In addition, as already

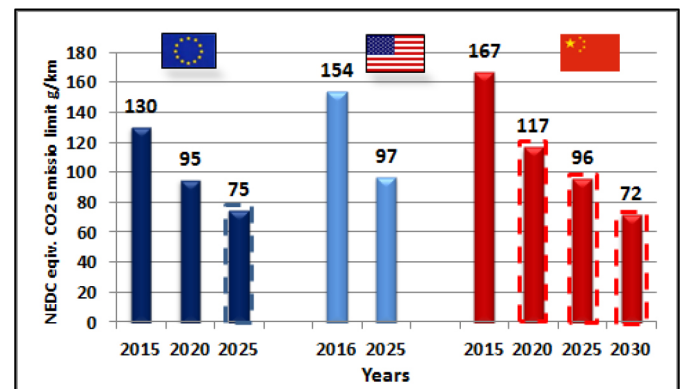
mentioned above, to consider the real use of the vehicle, TTW should also include useful energy not used for traction, leading to a more significant variable, that is the Tank-To-Use (TTU) efficiency:

$$TTU = \frac{\text{Energy Used in Vehicle}}{\text{Energy Taken from Tank}} \quad (2)$$

Moreover, a more detailed evaluation should include both the production efforts and the user scenario, such as the proportion of short/long distances, the intermediate charging as well as the supply of raw materials and recycling [15].

The analysis of the impacts on CO₂ emissions of different types of powertrain using the approach just described, will be presented in a future work.

After highlighting the importance of powertrains that include an internal combustion engine, it is necessary to evaluate how they can cope with the more and more stringent regulatory constraints, relating to CO₂ emissions and toxic gases, as detailed in [4]. It should be considered that there are significant differences in the various world markets, and after year 2020 the scenario is still uncertain, as summarized in Figure 4.

Figure 4. Trend of CO₂ emission legislation (dashed lines are only forecast)

Lower CO₂ emissions may be achieved by reducing fuel consumption, or by using fuels with smaller carbon content, such as bio-fuels or natural gas [14]. Furthermore, the efficiency increase should proceed in parallel with the reduction of toxic emissions, both during regulated driving cycles and real driving conditions [4]. These constraints are the main challenges confronting the design and development of new internal combustion engines, together with safety, comfort, drivability/performance, and costs.

Downsizing concepts, including turbocharging in combination with direct injection, have significantly contributed to the recent improvements of internal combustion engines [15, 16, 17, 39]. Among these, gasoline engines, operated with stoichiometric mixture, appear particularly promising for the simultaneous reduction of fuel consumption and toxic emissions. The Three-Way-Catalytic converter is a well-proven, affordable and very efficient after-treatment system. Diesel engines are more efficient, but NO_x and PM reduction is much more complex, expensive and potentially highly impacting on

user use since the SCR system will be used more frequently to respect the new NO_x limits under real driving conditions, thus requiring urea refills more often [18,19].

Nonetheless, SI engine efficiency is still to be significantly increased to respect the next and future CO_2 regulations. To better identify and understand the most effective technologies that could be introduced or adopted, one should firstly focus on the main limiting factors affecting efficiency and transient response. Referring to Figure 5 and [34, 35]:

- pumping losses at partial loads in zone n.1;
- limited thermodynamic efficiency due to reduced compression ratio, to avoid knocking damages at high loads, mainly in zones 2 and 3;
- combustion chamber and exhaust system thermo-mechanical stresses at high loads load in zone n.4 where an enrichment of the mixture is necessary to protect the engine components such as the turbine;
- turbo-lag for turbo-downsized engines, in zone n.2 where scavenging strategies should be adopted with negative effects on the Three-Way Catalyst (TWC).

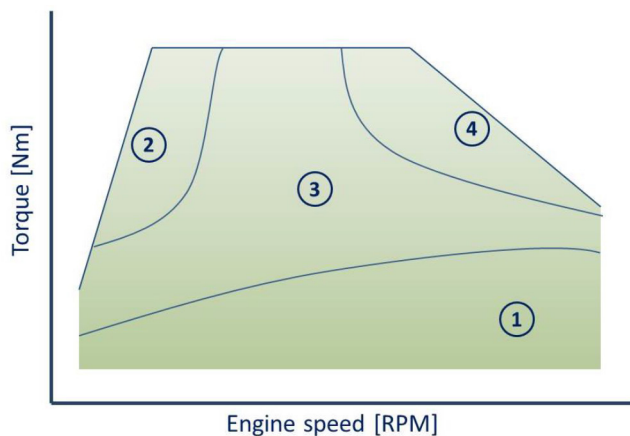


Figure 5. Strategic zones of improvements for SI Engine

This paper presents a conceptual comparison among the most promising technologies for SI engines, considering their effectiveness, their technological maturity and their impact on powertrain production costs. The considered timeframe horizon is 2025, and for brevity, this work will focus on powertrains designed for C-segment vehicles, which constitute the largest portion of the market, both in European and emerging markets.

The main investigated technologies are related to combustion management and air charging systems, the key elements for improving the previously mentioned limiting factors. To develop an objective comparison of the possible benefits, the evaluation criteria have been defined based on the requirements described in the previous paragraphs, and considering the most promising powertrain architectures. Different powertrain electrification levels have also been considered, thus implying different operational requirements for the internal combustion engine.

Below, a general overview of this work is provided. The main objective is twofold: technological assessment for SI ICEs, and definition of a methodology to objectify the comparison between technological solutions for complex powertrain architectures.

The first section presents a detailed analysis of the powertrain requirements, using a Quality Function Deployment (QFD) with a modified and personalized approach [20, 21]. Two vehicle concepts have also been considered, namely human-driven and computer-driven, by integrating and providing more details than what has already been published, for example in [23]. Indeed, semi-autonomous and autonomous driving systems will be progressively introduced in the market, and therefore the analysis of their impact on future powertrains cannot be ignored. The following section introduces the key powertrain architectures to achieve the desired targets, and focuses on their impacts on the internal combustion engines. Finally, evaluation criteria for a quantitative comparison are defined.

Then the different ICE technologies are described and critically analyzed, highlighting their effectiveness versus the main requirements. Such considerations are mainly based on the most significant technical and scientific literature.

The subsequent section introduces a simplified ICE-Vehicle model, which has been used to validate and integrate bibliographic data, and to further extend the analysis, to consider technologies and vehicle-powertrain architectures that could not be found in the literature. The attention is then mainly focused on technology costs, with a 2025 timeframe constraint.

A comparison among the most promising technologies for SI engines is finally presented, by making use of a selection matrix that defines the overall ranking based on benefits/costs ratio.

NEW POWERTRAIN AND ENGINE REQUIREMENTS

To define the requirements of the new powertrain architectures, a modified QFD approach has been used. QFD is an effective way to link the requests and needs perceived by the end-user point of view to the technical features of a product. Specifically, needs are evaluated by the users at the vehicle high level, therefore a multi-level QFD approach, as in [20], is used, until the powertrain level is reached, where engine and other powertrain components are evaluated. A brief illustration of the process is given in Figure 6.

User's needs and their priority (1-low, 7-high), can be obtained from market research and they represent the inputs for QFD. Specifically, in HoQ1 (house of quality, level 1), driver's needs are evaluated in an objective way by means of engineering variables. For instance, the demand for high performances can be objectified by the maximum vehicle speed, its acceleration or the time from 0 to 100 km/h. Table 1 shows the measurable requirements, which, in turn, represent the inputs for the second level, coming from driver's point of view.

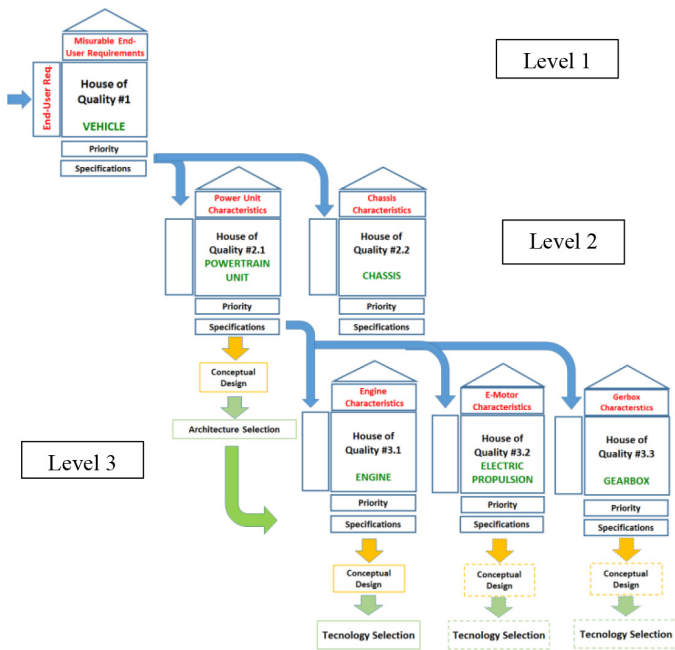


Figure 6. Multi-level QFD, from Needs/Wants of End-user to Powertrain Technical Characteristics

Furthermore, requirements can be divided in two sub-groups, both for standard and autonomous vehicles:

- explicit requirements by end-user;
- requirements from legislation related to CO₂ and toxic emissions, which are considered implicit by the end-user.

Legislation requirements are clearly of great importance because vehicle needs to fulfill them to be saleable. They are not explicitly considered by the user although their impact on customer's choice is becoming greater due to the driving bans imposed in many cities to the vehicles complying with old legislations.

Furthermore, the requirements for autonomous vehicles change, as already shown in [23]; specifically, the requirements related to performances (such as vehicle speed or acceleration time) become less important. The opposite is true for those related to comfort, such as NVH, torque regularity, vibration.

However, the constraints on CO₂ and toxic emissions remain at high priority and are the main driver of the technological change requested to new vehicles and powertrains.

The priorities and requirements targets in Table 1 depend on the vehicle segment, legislation standards and the manufacturer position among the competitors. Moreover, it is important to underline that costs are not considered here. The reason is that cost is one of the main requirements for the end-user and its weight would not be enough important if considered at this level. It instead will be considered by means of the *Technology Value Ratio*, as defined in the section *Results of Engine Technology Comparison*.

Table 1. Measurable Powertrain Requirements and Priority from HoQ1

	Needs/Requests		Measurable Needs and Request (from HoQ1, Vehicle Level)	Priority from MR		Unit
				Vehicle Controlled by Driver	Autonomous Driving	
End-User	Low Noise	1	Noise Emission Level	4	5	[dB]
		2	Accel. Time 0 → 100 Km/h	3	2	[sec]
		3	Accel. Time 80 → 120 Km/h (elasticity)	3	2	[sec]
		4	Max Vehicle Speed	3	2	[km/h]
	High Performance	5	Accel. Time 0 → 50 Km/h (direct transmission)	4	2	[sec]
		6	Time w/o acceleration during load Req.	4	5	[ms]
		7	Low Vibration	4	5	[dB]
		8	Cabin Comfort	4	5	[°C] & [hum]
	High Reliability	9	Mileage w/o failure	4	5	[km]
		10	Energy Refilling autonomy	5	5	[km]
	Easy to use	11	Maintenance interval/cost	4	5	[km]
		12	Energy Refilling Time	4	4	[min]
Standards	Low Fuel Consumption	13	Fuel Economy	4	5	[km/l]
		14	Toxic Emission according to Standard (WLTP and RDE)	7	7	[mg/km]
		15	EOBD/OBD2 compliance	7	7	[mg/km]
	Low Emission	16	CO ₂ according to Standard	7	7	[g/km]
		17	Mileage w/o critical event	7	7	[km]

As mentioned before, this work refers to a C-segment vehicle and regulation standards on emissions and fuel consumption by 2025 as shown in Figure 4. The priorities were introduced based on the study [22], adjusted with Magneti Marelli internal analysis.

On QFD level 2, in HoQ2.1, the requirements and priorities for the powertrain, described in Table 1, are mapped with their technical characteristics in Table 2, with appropriate specifications to effectively satisfy the requirements. In Appendix 3, the HoQ2.1 correlation matrix is illustrated. In Table 2, the priority specifications in case of driver or driverless vehicle as well as the most significant differences between the two cases are reported. The relevance of the different characteristics is highlighted by the green histogram on the left. Among all, the powertrain weight, including the contribution of the energy storage system, represents the most important factor in addition to the energy generation efficiency for the propulsion. Among the technical characteristics with higher ranking, it must be noted that the energy refilling time is critical for pure electric powertrains but not for hybrid ones. Clearly, emissions still have a crucial role. In case of vehicle with autonomous driving, the powertrain characteristics related to the performances are less important, whereas the comfort features are more relevant. This is true in case of the vehicles being used exclusively in driverless mode.

The reported characteristics and their targets are the inputs for the next phase of definition and selection of the powertrain architecture.

Table 2. Powertrain Technical Characteristics and relevance from HoQ2.1

Relevance histogram (HD)	Powertrain Characteristics (from HoQ2.1)	Relevance (0+100)		Unit
		Human Driving	Auton. Driving	
1	Powertrain Noise Level	10	13	[dB]
2	Powertrain Time to Full Power	15	9	[s]
3	Low-end Torque (at wheel)	20	14	[Nm]
4	Speed Range of High Torque	16	9	[rpm]
5	Maximum Power	21	14	[kW]
6	Max Amplitude of Jerking Oscillation	10	11	[rpm]
7	Time w/o Torque delivery during load Req.	18	15	[ms]
8	Powertrain Vibration	13	16	[dB]
9	Tank to Wheel Maximum Efficiency	25	22	[%]
10	Tank to Wheel Efficiency at part/low load	29	24	[%]
11	NOx Emission according to RDE	14	16	[g/kwh]
12	HC/CO Emission according to RDE	16	18	[g/kwh]
13	Soot/PN according to RDE	15	17	[PN]
14	CO2 on WLTC	23	19	[g/kwh]
15	Heating Power	5	5	[kW]
16	Mech Power for Cooling	29	24	[kW]
17	Efficiency of Electric Power Gen.	21	18	[%]
18	Energy Storage Capacity	15	13	[J]
19	Energy Refilling Time	14	12	[min]
20	PWT hours w/o failure	15	15	[h]
21	Firing Risk Recovery time	16	17	[ms]
22	Extra Torque Recovery Time	16	17	[ms]
23	PWT on board Failure Detection Time	20	23	[ms]
24	Fuctions/Components failure prevention	22	25	[num]
25	% Braking energy recovered	23	21	[%]
26	PWT Size	5	8	[Lit]
27	PWT Weight	38	35	[kg]

POWERTRAIN AND ENGINE ARCHITECTURE

ICE technical features and powertrain requirements depend on the architecture chosen for the analysis. As shown in the previous chapter, efficiency (tank to wheel) is one of the key features of the powertrain and electrification is one of the most effective ways to improve it. Several architectures exist [24], however the main ones are summarized in Figure 7. From B to F, the degree of electrification of the powertrain increases, which implies a greater availability of electrical power with respect to the total power used for traction and an higher pure electric mileage range. In hybrid vehicles, the electric machine can be mounted in different positions and can be used for different functions. In Figure 7, the electric machine positioning and the power flows for propulsion and kinetic energy recovery during braking, which represent a key feature to improve the efficiency of the vehicle, are highlighted. Electric machine positioning is denoted by P0/P1/P2 or P3. P0 means that the Electric Motor (EM) is coupled to the crankshaft via a belt in a configuration known as Belt Starter Generator (BSG). When the EM is in P1 position, it is directly coupled to the crankshaft by a toothed wheel or a chain. P1 configuration allows reaching a higher maximum torque than the belt driven electric machine, due to the higher power from recuperation and the more robust connection. In P2 configuration, the EM is located upstream the transmission between two clutches, in parallel to the ICE. P2 configuration allows the functionality of pure electric driving, with higher fuel consumption saving than P0/P1 architectures. The torque delivered by the EM is limited mainly by

the maximum torque of transmission, hence in case of contemporary use of ICE and EM, the gearbox must transmit the sum of the torques delivered by the two machines. In the P3 architecture, the EM is connected in parallel to the ICE downstream the gearbox, without any adaptation, and typically a BSG (> 4 kW) is also adopted in P0/P1 position to charge the battery during engine stops. In all previous hybrid configurations, the worse efficiency regions of ICE at part load can be avoided, leading to a lower fuel consumption. Furthermore, braking energy recovery can be performed.

In the so called Mild Hybrid powertrain (typically P0 and P1 configurations), the EM cannot drive the vehicle in pure electric mode, however it can support the internal combustion engine. P0 configuration main advantage is low cost integration, however P1 allows higher torque density.

In Full Hybrid powertrain, the most effective solutions are P2 and Power Split. In Power Split (configuration E), ICE is connected at the same time to the generator and the electric motor by a planetary gearbox, and the motor shaft is connected to the wheels with a final gear reduction. Power split concept combines features of both series and parallel hybrid. Full hybrid can be obtained also in P3 configuration (scheme D), with the highest energy recuperation potential.

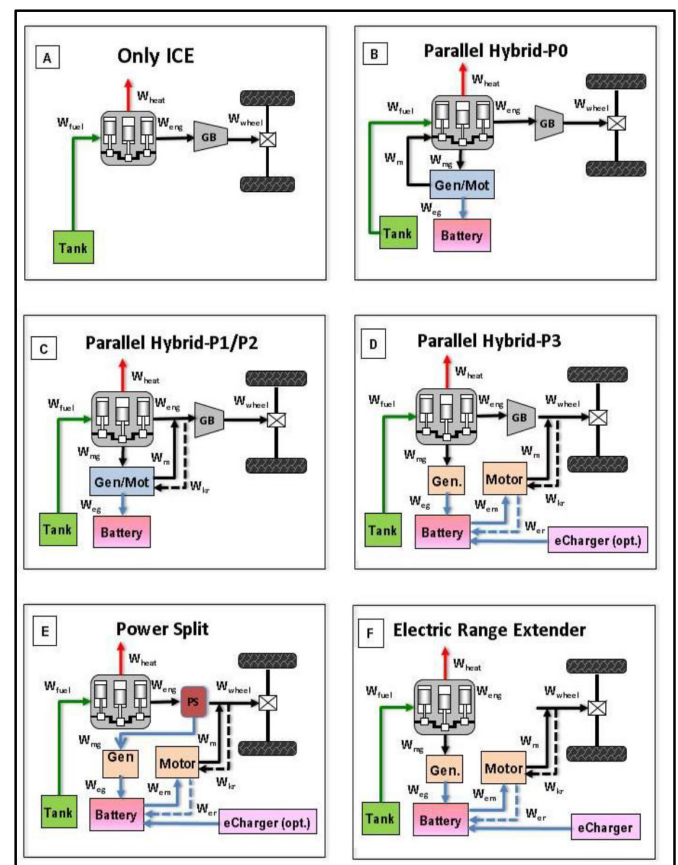


Figure 7. Powertrain Architectures with different electrification degree

Scheme F in Figure 7, describes a serial hybrid, where ICE operates as a range extender of the autonomy. The battery capacity allows to cover, without recharge, a longer distance than for a parallel hybrid (>250

km). ICE and generator have typically very high efficiency in a limited operating area [43] and rate power lower than 50% of the electric traction motor, depending on vehicle class and battery capacity.

The architectures from C (only P2) to F can be plug-in, with the possibility to recharge the battery like a pure electric vehicle. The functions of each described architecture are summarized in Table 3.

Table 3. Functions in hybrid electric powertrains

Functions	ICE	P0 Belt 12V	P0 Belt 48V	Hybrid P2/P3, Power Split	Hybrid Plug-in	Range Extender EV
Cold Start	Y		P	Y	Y	Y
Stop & Start	Y	Y	Y	Y	Y	Y
Coasting	Y*	Y	Y	Y	Y	Y
High Efficiency Electric Power Generation		Y	Y	Y	Y	Y
Regenerative Braking		P	Y	Y	Y	Y
Torque Assist		P	Y	Y	Y	-
Electric Take-off			Y	Y	Y	Y
Electric Driving				Y	Y	Y
Plug-in Electric Charging					Y	Y

* with e-clutch or AMT/DCT

Y=Yes P=Partially

Using the selection matrix, described in Table 2, a comparison among the most interesting variants of the proposed architectures is performed using the technical requirements described before as selection criteria. In the selection, the values of the technical specifications have been disregarded, considering the capacity of each architecture of satisfying the requirements. Focusing on C-segment, the reference powertrain consists of a 4-cylinder GDI turbocharged engine with a 6-speed DCT gearbox.

In [61], a comparison between P2 hybrid and Power Split architectures is shown and it is considered to define the selection matrix. In Table 4, architectures from 2 to 6 have a growing score due to the electrification, however they are characterized by rising costs due to the increased complexity and the larger size of the battery, which is necessary to ensure a long range in purely electric mode.

Moreover, as underlined by the high score, electrification affects not only the overall efficiency of the powertrain but also NOx as well as Soot/PN emissions. Indeed, the required torque is shared between electrical motor and internal combustion engine, and EM may relieve ICE during transient phases, where EGR management (internal or external) is critical, allowing the reduction of NOx peaks. Clearly, the impact of the electrification is higher when the proportion of the torque assigned to the EM is higher, which happens for HV configurations. As a matter of fact, the presence of TWC when ICE operates in stoichiometric conditions reduces the global ranking in the selection matrix.

Table 4. Selection Matrix for Powertrain Architectures

	POWERTRAIN ARCHITECTURES	Relevance (0-100)	1	2	3	4	5	6
			ICE GDI Turbo + DCT	Hybrid P0/P2 48V	Hybrid P2 HV	Hybrid Power Split HV	Hybrid P2/Power Split Plug-in	Range Extender EV Plug-in
	Powertrain Characteristics (from HoQ2.1)	Human Driving						
1	Powertrain Noise Level	10	1	2	3	7	7	7
2	Powertrain Time to Full Power	15	3	5	7	9	9	9
3	Low-end Torque (at wheel)	20	3	7	7	9	9	9
4	Speed Range of High Torque	16	5	7	7	9	9	9
5	Maximum Power	21	9	9	9	9	9	9
7	Time w/o Torque delivery during load Req.	18	5	7	7	9	9	9
8	Powertrain Vibration	13	1	2	3	7	7	7
9	Tank to Wheel Maximum Efficiency	25	5	5	7	9	9	9
10	Tank to Wheel Efficiency at part/low load	29	3	7	9	9	9	9
11	NOx Emission according to RDE	14	1	3	5	5	5	5
12	HC/CO Emission according to RDE	16	5	7	9	9	9	9
13	Soot/PN according to RDE	15	1	3	5	5	5	5
14	CO2 on WLTC	23	5	7	7	7	9	9
15	Heating Power	5	9	9	9	9	9	7
17	Efficiency of Electric Power Gen.	21	5	5	5	7	7	9
18	Energy Storage Capacity	15	7	7	7	7	5	7
19	Energy Refilling Time	14	9	9	9	9	5	3
25	% Braking energy recovered	23	0	5	7	7	7	7
26	PWT Size	5	7	5	5	3	3	3
27	PWT Weight	38	7	5	5	5	3	3
PWT Architecture Ranking [0+100]			55	72	82	93	89	90

The plug-in penetration in C-segment is expected only after 2025 to fulfill the CO₂ requirements. Indeed, as it will be shown in the next sections, CO₂ targets to 2020 and 2025 can be reached for C-segment vehicle by improving internal combustion engine efficiency and by a 48V electrification.

ENGINE TECHNOLOGIES DESCRIPTION AND ANALYSIS

This chapter summarizes the most relevant technologies for SI-ICE highlighting their advantages and the main drawbacks. The considered technologies can be classified according to the engine subsystem, as described in the following table:

The aforementioned technologies have been chosen for their degree of maturity with respect to the horizon of year 2025; moreover, they are considered the most effective for overcoming the limits of SI-ICEs, exposed previously.



Engine Subsystem	Technologies
Combustion System	GDI Lean Combustion Miller/Atkinson Cycle Variable Compression Ratio Water Injection Cylinder Deactivation
Air System	External EGR Multistage Air Charging

Furthermore, the technologies to reduce ICE mechanical friction and the power from auxiliaries, especially in the regulated cycles when the system starts from cold conditions, can be considered already state-of-art in many applications. They can be summarized as follows:

- electrification of coolant and lubricating systems, allowing to optimize pumping requirements for the coolant and oil, depending on the real needs of the engine, in contrast with non-variable mechanical pumps; furthermore, the combination of the electrification with split cooling, allows the engine to achieve warm conditions sooner, while the charge air cooler is kept colder in order to keep the filling efficiency at an appropriate level.
- crankshaft offset adjustments, bearings design or steel pistons (instead of aluminum).

After-treatment systems are not considered in this work because the options are quite defined; in case of stoichiometric combustion, the after-treatment system is composed of a three-way catalytic converter (TWC) in addition to a gasoline particulate filter (GPF); in case of lean combustion another catalyst to reduce NO_x , such as SCR or LNT must be added. Furthermore, the benefits achievable with biofuels are not considered in this work and they will be investigated in future works.

GDI Lean Combustion

Lean combustion in gasoline engine has proven to significantly increase the overall efficiency [35]. Unfortunately, expensive exhaust after-treatment is necessary because the three-way catalyst cannot reduce NO_x in case of excess of oxygen in the exhaust gas. To mitigate the catalyst cost increase, engine has to operate in extreme lean conditions (e.g. $\lambda > 1.8$), thus obtaining a drastic reduction of engine out NO_x emissions and further engine efficiency improvement, thanks to the higher ratio of specific heats and lower heat losses to the cylinder walls. Figure 8, from [32], is an example of the operating modes of a lean concept in the engine working points, highlighting the operating range in the WLTC cycle.

In addition to the increased demands on the charging system, further challenges arise with the extreme lean operation. The ignition of the diluted mixture is strongly hindered by the poor thermal boundary conditions that might lead to misfiring, therefore ignition system technology development is often required. An additional limitation under lean conditions is the increased cycle-to-cycle variations (CoV) due to the slower combustion. CoV can be minimized with higher turbulent combustion velocity by enhancing the in-cylinder charge motion. Hence, port and combustion chamber design as well as the spray pattern layout play a key role in the development of extreme lean combustion concepts. Furthermore, the transient operations including the switching between operating modes, e.g. from stoichiometric to

lean air/fuel ratios or vice-versa, have to be properly managed. As for all lean gasoline engines, the control of NO_x emissions remains a challenge, therefore LNT or SCR solutions are needed. LNT was already employed at end of the '90s in the first vehicles (Toyota, Mitsubishi, VW) equipped with GDI lean engines, and in the recent years it has been widely adopted in diesel engine applications.

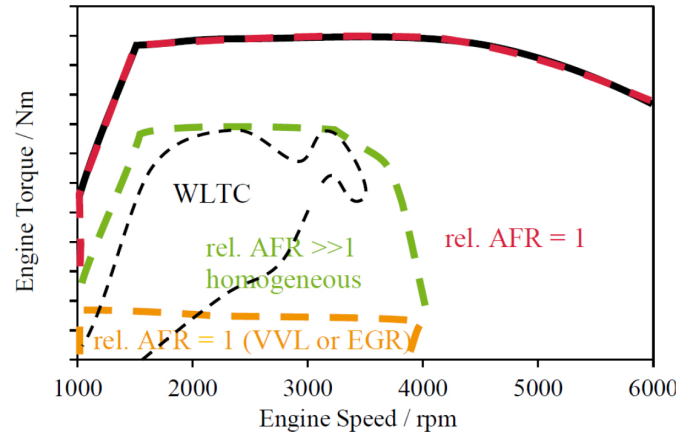


Figure 8. Lean concept operating modes in engine working points (Source: [32])

In [33], Ricardo shows a lean burn combustion concept that uses spray guided lean stratified operation. NO_x emissions control is carried out by means of a Lean NO_x Trap (LNT) catalyst. The study highlights the BSFC improvement achievable in stratified lean burn conditions (2.0 L turbo, 200 kW rated power) for a D-segment vehicle. Over NEDC, the solution has been simulated producing a 14% reduction of CO_2 emissions compared with the equivalent stoichiometric turbocharged GDI engine, considering LNT regeneration. Over WLTC, the fuel consumption reduction is 12%.

Miller/Atkinson Cycle

Miller-Cycle describes a combustion system with early or late intake valve closing [30, 41, 47, 49, 51, 63]. Figure 9 illustrates the two possibilities used to perform the Miller cycle.

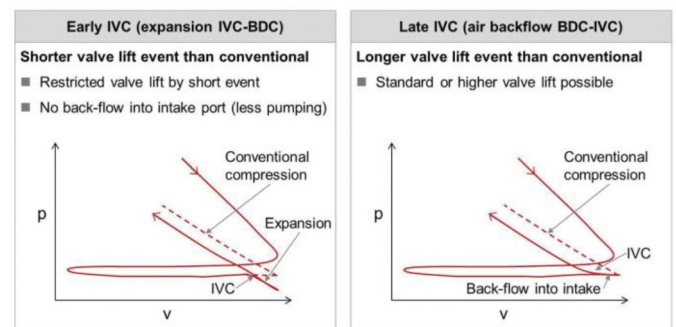


Figure 9. Miller cycle early and late Intake Valve Closing (IVC). (Source: FEV 2015)

Miller cycle is based on Otto cycle, having an expansion stroke which is longer than the compression stroke. In late intake valve closing Miller cycle (LIVC), the intake valve is kept open during a significant part of the piston movement during compression, so that part of the mixture contained in the cylinder is not scavenged into the manifold, allowing the reduction of mixture mass that is "trapped" in