POLITECNICO DI TORINO

Master's Degree Course in Mechanical Engineering

Master's Degree Thesis

Conversion of a newly patented pre-chamber spark ignition engine to run on hydrogen: state of the art of H_2 engines and preliminary investigation

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Academic Year 2020-2021

Summary

The recent growing attention to cleaner and more sustainable sources of power has led to an always higher importance of hydrogen in the automotive field. In this work, the main and more interesting properties of hydrogen are analyzed, together with the current technologies used to produce, store, and distribute it and the issues linked to them. An overview of the policies and incentives adopted by the European Commission to promote its use is also present. In particular, the path the European states should follow to reach the Union's goals is described. The attention of the work is directed to hydrogen internal combustion engines; hence the functioning, the strengths, and the weaknesses of both direct and indirect injection hydrogen ICEs are investigated. The second part is focused on the pre-chamber combustion system recently developed by Italtecnica. In this first phase, said engine is undergoing tests to verify its functioning with gasoline and its compliance with the current, and the upcoming, emission standard. Italtecnica's aim is to convert this engine to operate with hydrogen in the near future. Hence, after a deep analysis of this innovative combustion system, an analysis of the current emission regulation, together with its issues, and of what will most likely be the Euro 7 was made.

Acknowledgements

Throughout these years at Politecnico di Torino and the writing of this thesis I have received a great amount of support and assistance.

I would like to thank both my supervisor, prof. Ezio Spessa, and my tutor at Italtecnica, Ing. Carlo Cavagnero, for their guide and their precious advices during all the stages of this work.

My biggest gratitude goes to my parents and to my brother Alessandro, thanks to whom all of this was possible. I'm thankful for their tireless support and for their continuous encouragement, even though it wasn't always peacefully received.

Of course, I would like to thank my grandmother for always being my number one fan and an endless source of love (and food).

I would like to thank my American family as well. Despite the distance, their support and affection have been significant in the achievement of this goal, and will continue to be so for my future ones.

Finally, I would like to thank my flatmates, my classmates, my friends from home, and my Turin-friends for having kept up with me through it all. You all made these challenging years not only bearable, but the best and most important of my life.

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Chapter 1

Introduction

In a world scenario in which always more importance is given to the reduction of pollution and the attention to climate change issues, also and especially the automotive field has been moving towards more sustainable solutions. In this optic, the object of this work is the conversion of an engine currently running on gasoline into a more climate-friendly fuel, hydrogen. In particular, the engine in question is an innovative spark ignition gasoline engine designed by Italtecnica Srl, equipped with a pre-chamber combustion system, that is going under patent approval.

The first step has been a deep research on hydrogen, in order to understand the benefits of using it as a fuel, represented mainly by its unique properties and its non-polluting emissions, but also the roadblocks that are in the way for it to become popular in such applications. In particular, it has been investigated in detail its ways of production, distribution, and storage, which are still object of much research. Moreover, a look into the policies adopted by the European Commission in order to develop a hydrogen economy and to reach the aim of climate-neutrality set for 2050, was taken.

As part of this deepening on hydrogen as a fuel for the automotive sector, a portion of the research was carried on the different possible ways in which hydrogen can be used to propel a vehicle. In particular, the focus has been on hydrogen internal combustion engines and therefore, their pros and cons in comparison to hydrogen fuel cell vehicles, that are more popular in the current European scenario. The main characteristics and issues of H_2ICEs were illustrated, whether the injection of the fuel is direct or indirect.

The research later moved onto the pre-chamber combustion system. An overview on its patents history and its developing over the years was made, together with its different ways of implementation, namely whether the pre-chamber is active or passive. It follows a deep description of Italtecnica's new invention: where the innovation relies, the description of the design, how it works, and which are the benefits from its use.

Lastly, a deepening on the new upcoming Euro 7 emission regulation was made, in order to understand how the European scenario is moving and to have a clue on what new vehicles will need to comply with it. Starting from the current Euro 6, its main weaknesses and lacks were described, together with the possible solutions and improvements that different European institutions and associations, working for and with the Commission, brought forward. In particular, the focus has been on the work done by AGVES and on the results it presented, as the starting point for the profiling of said new standards.

Chapter 2

Hydrogen

In the recent years, hydrogen has been largely proposed as a possible alternative to traditional fuels to be used in internal combustion engines. The search for cleaner and more sustainable sources of power in order to tackle the issue of climate change has made this possibility even more tempting. The most interesting fact of using hydrogen with ICE is that there are not any pollutants resulting from its combustion, making it a near-zero emissions fuel. Furthermore, thanks to the properties of hydrogen, H_2ICEs can operate with a higher efficiency compared to that of conventional ICEs.

The benefits from the use of hydrogen as a fuel for internal combustion engines are clear and will be hereby explained in detail, what is also important to analyze is how hydrogen is produced, transported, distributed, and stored. In fact, in order to appropriately appreciate the assets of hydrogen in comparison with conventional fuels, it is important to follow a well-to-wheel approach. In this optic, to properly be a near-zero emissions engine, a H_2ICE needs to work with a fuel that also results in close-to-zero emissions during both its production and transportation processes.

In order for hydrogen economy to kick off and for hydrogen-fueled vehicles to be appealing to both consumers and carmakers, many steps ahead in different fields need to be done. In fact, to reach these goals, first of all hydrogen production and distribution need to be sustainable and, at the same time, economically viable, in order to actually represent an alternative to traditional fuels. Also, an effective, economically acceptable, and safe way to store hydrogen needs to be developed.

To make this transition to the hydrogen economy smoother, many measures have been taken by both national governments and the European Commission. Actions have been taken, especially at a European level, to promote investments in hydrogen technologies by energy and automotive companies and also to encourage consumers to embrace this new way of mobility. In this optic, milestones have been set to be gradually achieved while the maturity of this growing market is reached. The main and most recent strategies adopted by the European Commission are hereby illustrated.

2.1 Properties of hydrogen

The scope of this section is to explain the most relevant properties of hydrogen, specifically as a fuel for automotive applications equipped with both an internal combustion engine and fuel cell. First of all, the properties that make hydrogen a fuel with a big potential in the field are as follows. [1]

- Wide flammability range: it can be burned over a wide range of air-to-fuel ratio, meaning it can also run on a lean mixture and this leads to lower peak combustion temperatures and hence less nitrogen oxides. It must also be taken into account that mixtures that are too lean lead to limited power outputs.
- High autoignition temperature, resulting in higher compression ratios achievable without any combustion anomalies (such as knock).
- High flame travel velocity: at stoichiometric operation this is 1.9 m/s, almost 6 times higher than that of gasoline. As a result, the combustion is more isochoric and thermodynamically more favorable. However, as the mixture gets leaner this value decreases.
- An octane number (RON) >130, resulting, again, in higher compression ratios achievable and therefore, higher brake thermal efficiencies and power outputs.
- Thanks to its high kinematic viscosity, thermal conductivity, diffusion coefficient and low density, hydrogen has an improved ability to disperse in air.
- Low ignition energy: a small amount of energy is needed to ignite hydrogen, allowing it to properly ignite even under lean operation and to avoid problems in cold start situations.

- As previously said, its carbonless structure results in a combustion without the production of any CO_2.

On the other hand, hydrogen has some limitations as well which result in major drawbacks for automotive applications and for which some remedial actions are to be taken.

- Low energy density: hydrogen has the lowest energy density among competitive fuels, in fact, a large volume of hydrogen is required to produce an acceptable amount of energy.
- The stoichiometric air-fuel ratio of 34.33:1 on mass basis and of 2.4:1 on volume basis results in the fact that a considerable part of the combustion chamber is occupied by hydrogen (29.6%) instead of being filled with air. Hence, the maximum amount of energy in the cylinder and the maximum power decrease.
- Low ignition energy has both positive and negative outcomes: hot gases and hotspots can easily ignite the mixture, leading to early ignition.
- Small quenching distance: hydrogen can burn even in small and narrow clearances, such as crevices. This could lead to backfire when burning gases flow out of the crevices during the intake phase, causing the charge to ignite.
- High burning rate: higher pressures and temperatures are reached during the combustion (especially near stoichiometric), leading to higher NO_X emissions, noise and vibrations.
- Material compatibility: it is important to use materials that can withstand the extended contact with hydrogen in order to avoid problems.
- Hydrogen-air mixtures are sensitive to catalytic action, hence resulting in problems regarding safety and reduced control of the combustion process.

- Blowby water vapor condensation represents a higher risk of undesirable corrosion and lubricating oil contamination.

All in all, hydrogen can be seen as the ideal mean for the storage of renewable energy at different scales. This is, especially, due to its highest gravimetric energy density among other fuels, despite its quite low volumetric energy density [2]. For what concerns these two properties, the comparison between hydrogen and other fuels can be seen in Figure 2.1.

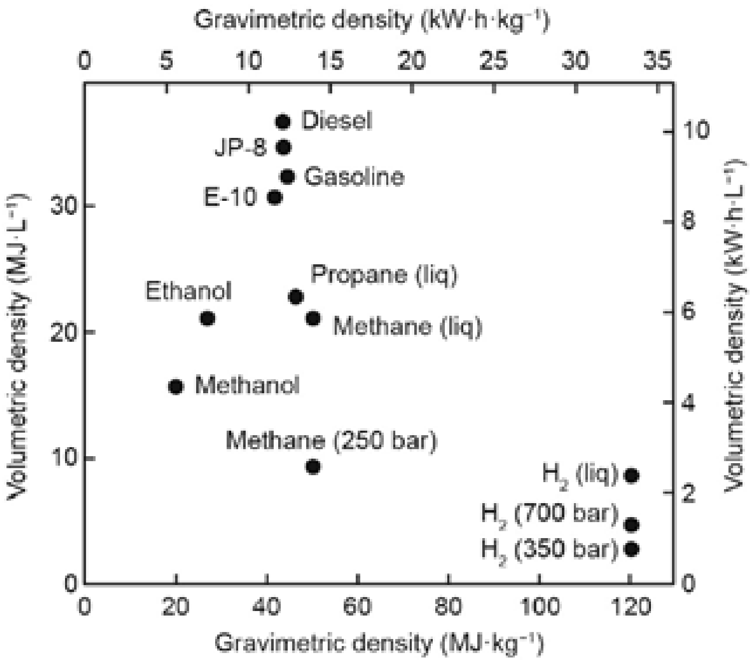

Figure 2.1: Gravimetric energy density and volumetric energy density of fuels. Credit: US Department of energy Fuel Cell Technologies Office [2].

Property	Gasoline	CNG	H_2
Stoichiometric AFR	14.5	17.2	34.3
Lower calorific value [MJ/kg]	44.4	50	120
Octane number (RON)	95	>120	>130
Minimum ignition energy [mJ]	0.29	0.2	0.02
Laminar flame speed [m/s]	0.3	0.45	1.9
Flammability limit %	1-7.6	5.3-15	4-75
Diffusivity	0.05	0.16	0.61
Auto ignition temperature [°C]	230-480	540	585
Energy density [MJ/m^3]	31.15	32.56	10.05
Quenching gap in air [mm]	2	2.03	0.64

Table 2.1: Main properties of hydrogen with regard to other popular fuels [1].

2.2 Production

Although hydrogen is abundant on Earth, it is always found as part of a compound, such as water or methane. Hence, to produce pure hydrogen it is necessary to single it out by means of chemical processes. The more traditional pathways for hydrogen production are: hydrocarbon reforming, hydrocarbon gasification, biomass reforming and water splitting. Hereby, the most common processes used are described [3].

- Steam methane reforming (SMR): a stream of natural gas or methane is reacted with steam and thanks to the presence of a catalyst, hydrogen and carbon dioxide are produced. More precisely, the product of this process is a gas made of typically 70-75% of hydrogen on a dry mass basis, small amounts of methane, carbon monoxide and carbon dioxide. Thanks to SMR favorable economics and the fact that it has the lowest CO_2 emissions along all fossil production routes, nowadays almost half of the global hydrogen supply is produced using this method. The main issue of SMR is the production of carbon dioxide and pollutants and the fact that it is not a sustainable process since it uses the finite natural gas reserves.

- Auto-thermal reforming oil: with higher hydrocarbons or when pure oxygen is available, partial oxidation (POX) is preferred. It offers a more rapid response and compactness than SMR, however, POX has a lower efficiency, hence, a lower concentration of hydrogen in the products.

- Gasification of coal and other hydrocarbons: coal reacts with oxygen and steam under high temperatures and pressures to form synthesis gas, made of hydrogen and carbon dioxide. Like SMR, this process dominates the production of hydrogen and it has the same issues.

- Electrolysis of water: water molecules are split into hydrogen and oxygen using electricity in an electrolyser device. It can be done at a wide range of scales, from few kW up to several MW. This process is usually limited to small scale production, since large hydrogen production plants are not economical. This process is preferred when high-purity hydrogen is needed.

In Figure 2.2 it can be seen the price of the hydrogen in relation to the quantity of hydrogen produced for three different ways of producing it. For each production process there are three possible curves, depending on the price of the energy carrier used to propel the process. As it was stated before, it can be appreciated that hydrogen produced through electrolysis results to be the most expensive one and its price is almost non-dependent from the quantity produced. On the contrary, other processes, which are not as sustainable as electrolysis, display lower costs, especially when high quantities are produced. [4]

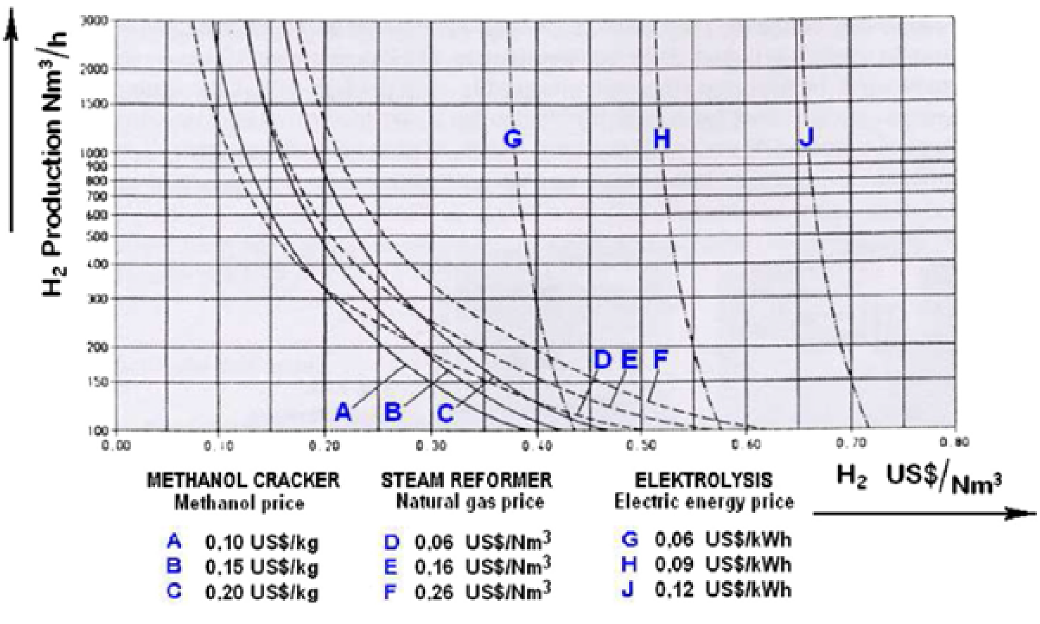

Figure 2.2: Hydrogen production costs [5].

Hence, non-renewable sources still excel in the production of hydrogen. More precisely, natural gas is the major source accounting for 48% of the total, followed by oil (30%) and coal (18%), while electrolysis only contributes for 4% of the total share. With the increase in natural gas prices, coal gasification is expected to become the most economical solution in the near future. Also, biomass gasification is very promising especially due to the fact that it is a renewable solution, however it is still at an early stage of development. Nowadays the cost of hydrogen is more than twice as much as that of diesel and petrol. Therefore, a substantial progress is needed to make hydrogen both environmentally sustainable and cost-competitive with traditional fuels. In fact, to fully benefit from hydrogen advantages such as cleanness, versatility, and efficiency, it must be produced from renewable sources. Based on the production process it comes from and on the energy source said process utilizes, hydrogen can be dubbed, in order of sustainability, grey, blue, green, pink, or yellow.

- Grey hydrogen: obtained from natural gas through SMR or ATR. At the end of these processes the CO_2 produced results as emissions in the atmosphere. Nowadays, 99% of the hydrogen produced for industrial use is grey.
- Blue hydrogen: obtained from the same processes as the grey one. However, the CO_2 that results as a byproduct is captured and stored through a process called Carbon Capture Usage and Storage (CCUS), by doing so the impacts on the environment are mitigated.
- Green Hydrogen: obtained from electrolysis which, in order to make the hydrogen green, needs to use electricity that comes from renewable energy such as wind or solar. This represents the cleanest option available.
- Pink hydrogen: as the green one, it is obtained through electrolysis which in this case is powered by nuclear energy.

- Yellow hydrogen: as the green and the pink ones, it is obtained through electrolysis that in this case uses electricity coming from solar energy.

In Figure 2.3 the estimated price of grey, blue, and green hydrogen through 2030 is plotted. As it can be seen, green hydrogen price will be the highest at the beginning, but it will progressively decrease while the price of the other less-clean types will increase.

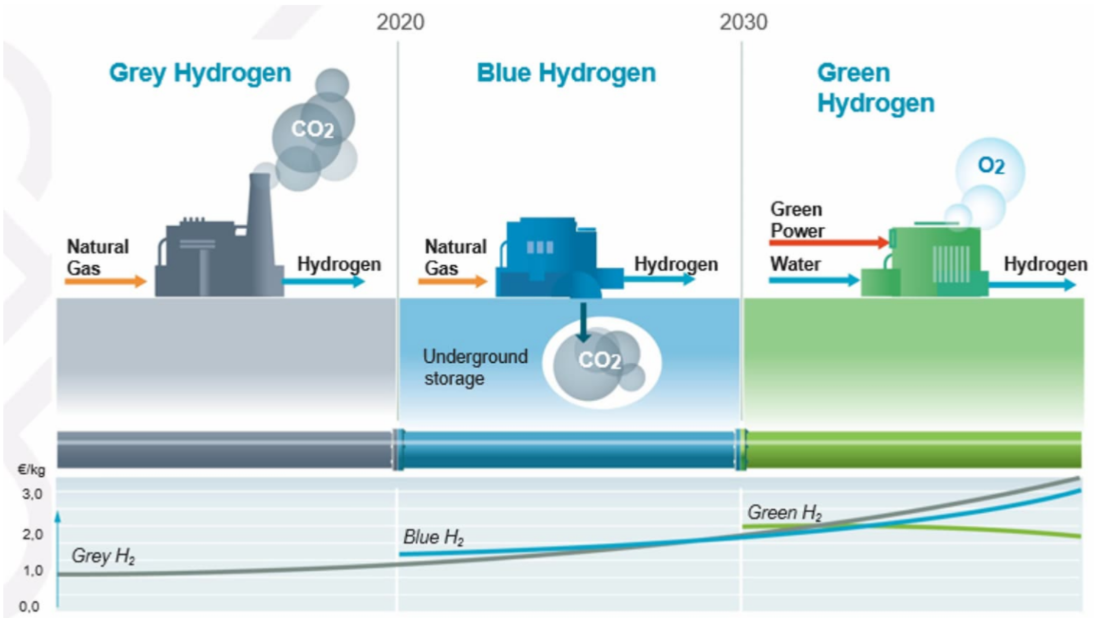

Figure 2.3: Scheme of the price of grey, blue, and green hydrogen through 2030. Credit: tno.nl.

2.3 Distribution

In order for hydrogen mobility to catch on there is the need of an infrastructure capable of delivering hydrogen from where it is produced to the dispenser, either at the refueling station or at the stationary power generation facility. This is an important issue, especially in the period of transition towards the hydrogen economy. In fact, there is the crucial need of an efficient and safe transportation and distribution network that could reach refueling station across the countries. Hydrogen distribution is a critical issue also because it contributes to the cost of the fuel and to the energy used and the emissions associated with the delivery. Furthermore, the choice of the most suitable solution relies on individual geographic and market features.

There are several possible solutions to transport hydrogen: cryogenic liquid tankers, pressurized hydrogen tube trailers, gas pipelines and hydrogen carriers. Each of the previous solutions has its issues that mainly consist in high operating costs for large-quantity transportation, energy inefficiency for liquefaction and high capital costs for the construction of a pipeline system. During the introductory period, in which the demand for hydrogen will be relatively moderate, tube trailers could represent the best option. Afterwards, to meet the demand of the hopefully growing market, cryogenic trucks with their larger capacity will be more suitable. Once a high demand is reached, a pipelines system that brings hydrogen to high demand areas is the best option. In fact, pipelines would greatly increase the transport capacity, in front of a higher investment: heat-insulated pipes, pumping systems, and cooling systems are necessary. However, the issues tied to pipelines are several. First of all, to justify the massive investment needed to build the infrastructures for an efficient and wide grid, hydrogen mobility needs to become more viable and to increase its popularity. Hydrogen pipelines have costs of construction that are 10-20% higher than those of natural gas pipelines, which cannot be therefore used to transport high-pressure, pure hydrogen. The main problems are hydrogen embrittlement, hydrogen blistering and hydrogen-induced fatigue, therefore, it is strictly necessary to adopt the right material that could mitigate these drawbacks. Pipelines need to be perfectly thermally insulated, otherwise the air containing more than 50% of oxygen around them becomes extremely flammable [4].

An interesting strategy is to combine the existing natural gas pipelines with new pipelines to transport high-pressure hydrogen [2]. However, for all the reasons explained above, natural gas pipelines cannot be used to safely transport hydrogen without incurring in, even dangerous, problems. For this reason, a possible way to transport hydrogen while taking advantage of the existing natural gas pipelines is to add about 10-20% of hydrogen into the natural gas flow. This solution is technically feasible with almost no ignition risks, no increase in pipeline fatigue, no increased leakage risks, and it is economically acceptable. Downstream of the pipeline pure hydrogen can be obtained by means of several techniques which, however, at the moment are too expensive. For this method of transportation to be and actual effective way to bulk hydrogen, highly efficient and cheap separation techniques need to be developed.

2.4 Storage

First of all, it is important to underline that storage of hydrogen is necessary at different scales and at all the different steps of the supply chain. In fact, hydrogen storage is needed nationally as a strategic reserve, at production sites, at refueling stations, and on board of the vehicles. This is a crucial issue and the most critical one among all those hereby explained. To store a fuel in a vehicle it is fundamental that said containment is compact, light, safe and economically affordable. Making hydrogen storage a challenge is its extremely low density that would require huge on-board tanks in order to store acceptable amounts of usable energy.

Hence, there are three requirements that a material needs to satisfy in order to represent a solution to this issue: high hydrogen storage capacity, reversibility of the discharging/charging cycle to be compatible with present fuel cells, and fast discharging/charging kinetics with minimum energy barriers to hydrogen release and charge. Finding a material that could meet all three of these demands is challenging and furthermore, it must be taken into account that to be a viable storage material it also should satisfy the prerequisites of weight, cost, lifetime and safety. Nowadays, there are six methods by which hydrogen can be stored in a vehicle: high-pressure gas cylinders with a pressure up to 700 bar, liquid hydrogen in cryogenic tanks at a temperature of 21 K, adsorbed on materials having a large specific surface area at a temperature lower than 100 K, adsorbed on the interstitial sites of a host material at ambient conditions, chemically bonded in ionic or covalent compounds at ambient pressure or through the oxidation of reactive materials such as Li, Na, Mg, Al, Zn with water [3].

Currently, on vehicles hydrogen is stored either in gas form using high-pressure cylinder, a similar technology to that used for natural gas, or in liquid form in cryogenic reservoirs. In fact, this is the easiest and cheapest way. The issue with these current methods is the high energy penalty encountered at both compressing a gas and liquefying hydrogen, respectively up to 20% and 40% of the energy content of the fuel. Furthermore, both of these solutions concern the public in terms of safety and thus reduce their acceptability among the population. In addition, using liquid hydrogen requires a system with a higher complexity, especially in the distribution and supplying, thus increasing the associated costs. Plus, the low temperatures needed to store hydrogen in liquid form imply further considerable problems [3].

Storing hydrogen in micro-spheres made of glass is a technology that exploits the hydrogen permeability of glass at high temperatures. These micro-spheres can have diameters ranging from 25 to 500 mm, they are heated up to 200-400°C and contain pressurized hydrogen up to 340 MPa. This upper limit of the pressure is given by the resistance of the spheres. This is an interesting solution, especially for motor vehicles tanks, since the micro-spheres can be reused and because the issue regarding fuel leakages could be safely handled [4].

Another interesting solution is provided by the so-called metal hydrides. Some metal alloys have the ability, when pressurized, to bind with hydrogen and store its atoms within their crystalline reticulum through an exothermic process called hydrogenation. Therefore, metal hydrides are compounds of one or more metal cations and one or more hydride anions. They are classified according to their temperature of dehydrogenation, which is the process, that requires heat, through which they release hydrogen. The drawback of this technology is its weight: for the same weight, a vehicle that uses hydrides as storage has an autonomy three times lower than that of a vehicle using advanced tanks (either for liquid or compressed-gas hydrogen). Furthermore, due to the use of rare earths and therefore, of metal alloy availability, this solution is expensive [3].

Storage of hydrogen could be achieved also by means of carbon nanostructures, particular forms of carbon graphite aggregations which are able to capture and accumulate hydrogen. Nanostructures have a high hydrogen storage capacity and also a very low energy consumed for storage. This has been regarded as an interesting solution especially because it overcomes the issues correlated with metal hydrides, such as the necessity of heat for hydrogen release, a slow regeneration rate, a poor cyclability. However, while the first studies carried out in the 90's brought some promising results, these results were not confirmed by later research. In fact, the main drawback of carbon nanostructures is their insufficient storage capacity, especially at room temperature. Studies show that storage capacity of carbon nanostructures can be more than doubled by means of lithium doping. In fact, by adding lithium, the surface affinity of carbon materials is enhanced, thus allowing a higher physisorption: in this way storage capacity can increase up to 2-4 times [3].

2.5 Hydrogen policies in Europe

To foresee the future of hydrogen mobility it is important to learn about the policies and the actions taken by the different authorities. For example, it is interesting to learn what the European Commission has put in motion in order to make the hydrogen economy viable in the next few years, especially now that a sustainable mobility is considered an important goal to be reached as soon as possible.

In 2020 the European Commission published the so-called European Hydrogen Strategy [6], in which the path towards a not only hydrogen economy, but a renewable hydrogen economy is described. The goal of Europe is to reach carbon neutrality by 2050 and to implement the Paris Agreement, to do so they found hydrogen to be essential to this commitment. Nowadays the share of hydrogen in the EU's energy mix is less than 2%, but it is projected to exceed 13-14% by 2050. However, they recognize that, in order to be essential in the fulfilment of this goal, hydrogen production needs to both reach a far larger scale and become fully decarbonized. Almost all Member States have conceived plans for clean hydrogen, since renewable and low-carbon hydrogen are not yet cost-competitive. The ultimate goal for the European States is the production of hydrogen using mainly wind and solar energy, but in the short and medium term other forms of low-carbon hydrogen are needed to support the future of the hydrogen economy. To reach these goals, three phases have been identified in the years between 2020 and 2050.

- First phase 2020-2024: the strategic objective is to install at least 6 GW of renewable hydrogen electrolysers and the production to up to 1 million tons of renewable hydrogen. The infrastructures will still be limited as the demand for hydrogen will be primarily met by production on site. Transportation through blending with natural gas may occur. It will be necessary to start planning a medium range transportation infrastructure. Also, infrastructure for carbon capture and use for CO_2 is required.

- Second phase 2025-2030: the strategic objective is to install at least 40 GW of renewable energy electrolysers and the production of up to 10 million tons of renewable hydrogen. During this phase hydrogen needs to become an intrinsic part of an integrated energy system. Gradually, renewable hydrogen will become cost competitive. The retrofitting of existing fossil-based hydrogen production with carbon capture should continue to reduce greenhouse gas and other pollutants. The need for a wide logistical infrastructure will emerge in order to serve hydrogen to every area of the Union. A Pan-European hydrogen grid will be planned, along with a network of hydrogen refueling stations. Also, international trade of hydrogen will begin.

- Third phase 2030-2050: renewable hydrogen technologies should reach their maturity. Renewable hydrogen will be used at large scale and in all sectors.

In the same year, the European Commission published the Sustainable and Smart Mobility Strategy [7] as well, in which the Commission wants to identify a clear path towards a more sustainable, green, and resilient European transport system. In this document the Commission reaffirmed the importance of hydrogen in the achievement of this objective. More precisely at the point 22 of the document, it is made explicit the goal in terms of number of hydrogen stations. By 2025 half of the 1,000 hydrogen stations expected by 2030 are to be built: this represents just a first step towards a dense, widely spread network. At the same point it is said how the Commission will publish a strategic roll-out plan to outline further supplementary actions to support the development of alternative fuels infrastructures. Again, at the point 82 of the document, the Commission states that regulatory and financial instruments will be made available to ensure secure supply of materials and technologies indispensable for a sustainable mobility and to avoid Europe's dependence on external suppliers.

Previously, in 2019, the Fuel Cell and Hydrogen Joint Undertaking (FCHJU), of which the European Commission is a member, had released the so-called Hydrogen Roadmap for Europe [8]: a sustainable roadmap for the development of hydrogen energy towards 2050. More precisely, this document sets some concrete goals that need to be achieved by 2030. These goals, in terms of transportation, are a fleet of 3.7 million fuel cell passenger cars, 500,000 fuel cell light commercial vehicles, 45,000 fuel cell trucks and buses and 570 fuel cell trains. On the other hand, in term of infrastructure and hydrogen generation, 7,700 large refueling stations are expected, compared to the 152 existing in 2018 and 1/3 of the hydrogen produced is expected to be ultra-low carbon.

Chapter 3

Hydrogen mobility

Once the great potential of hydrogen as a fuel has been well-established, it is interesting to take under consideration the different ways it can be employed in the automotive field. In fact, while the use of hydrogen as a fuel in an internal combustion engine is a possible solution, it is not the only one. Hydrogen can be used in reaction with oxygen in a fuel cell vehicle in order to power an electric motor. Electric vehicles could be seen as superior in terms of low noise and zero engine-out emissions, on the other hand they display major drawbacks which could make them less appealing to both consumers and carmakers.

Fuel cells generate a small power output due to their power generation mechanism, thus making the solution less suitable for heavy cargoes transportation. By comparing the characteristics of torque and power output of an ICEV and a FCV this can be appreciated. As it is shown in Figure 3.1, while the power output line of an electric motor is drawn flat in order to avoid overheating, an ICE can produce a larger power output at higher engine speed and its torque is almost constant with the increase of the latter.

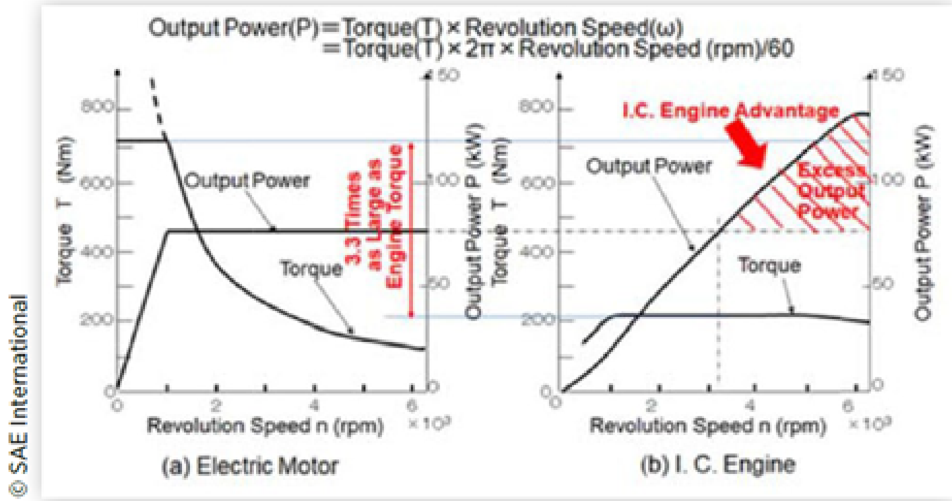

Figure 3.1: Comparison between ICE and electric motors of EV and FCV [9].

Furthermore, the fuel cell technology is relatively new and therefore it still requires new developments, which in turn require time and research. On the other hand, H_2ICEs follow the well-known concepts of traditional ICEs, concepts thoroughly developed over the past 100 years. In fact, H_2ICEs basically are the product of a combinations of features coming from both diesel and gasoline engines. Additionally, H_2ICEs are more suitable for high levels of mass production of the full range of vehicles since the whole production process along with the infrastructures needed are already on place and well-functioning. Also, they are more appealing to the average consumer because of their ability to produce higher power outputs, their lower cost and their high and robust quality. On the contrary, H_2FCVs display a delicate mechanism that represents a problem in terms of reliability and maintenance costs, they do not perform well at extremely low temperatures and they require the use of expensive and rare metals, such as platinum.

As it was previously mentioned, when its unique properties were being described, hydrogen represents the most promising alternative power sources in comparison with all the others. Especially in terms of large power output, lightness in weight and smallness in size. Additionally, its specific power characteristics are even comparable with those of fossil fuels, such as gasoline and diesel, as it can be seen in the graph in Figure 3.2. In fact, while gasoline and diesel have the ability to generate around 3.61 MJ/m^3, in case of hydrogen this value depends on the technology used for the formation of the mixture in the combustion chamber. In case of external mixture formation, a H_2ICE can generate 2.98 MJ/m^3, while with internal mixture formation, since the air introduced is 30% more, this value can reach 4.23 MJ/m^3. Hence, a H_2ICE with internal mixture formation can generate an amount of energy that is even 1.17 times larger than that of a traditional engine [9].

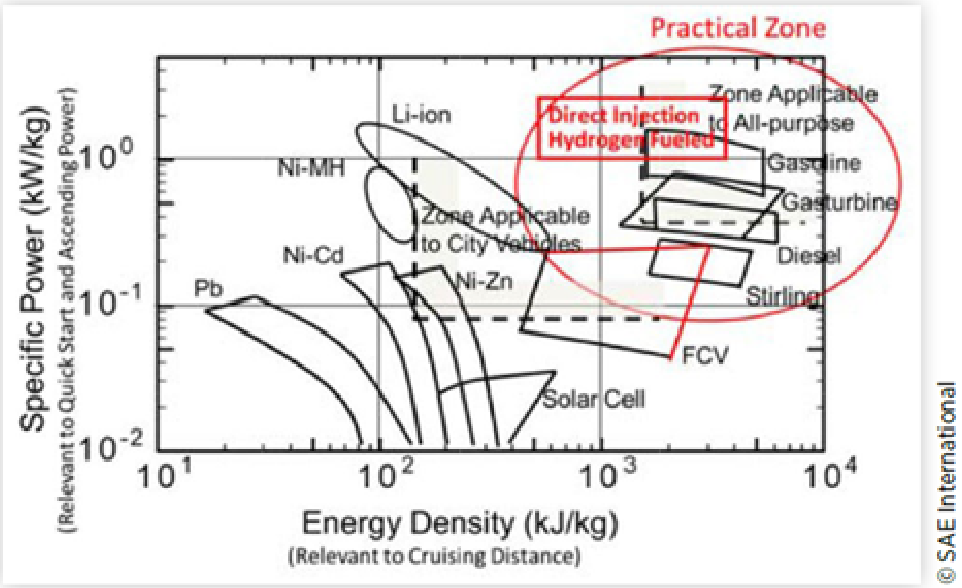

Figure 3.2: Comparison of various power sources in terms of energy density and specific power [9].

3.1 Port fuel injection H_2ICE

Due to the fact that an intake port injection system is easily adaptable on a conventional spark ignition engine, port fuel injection H_2ICEs have been more popular than the direct injection ones. External mixture formation is therefore the most common strategy but it can be employed in a number of variants that may differ in terms of part-load control, air-fuel ratio and charging strategy.

Crucial in the choice of the air-fuel ratio to be adopted are NO_x emissions. In fact, as it can be seen in Figure 3.3, there is a strict correlation between these two factors: for lean mixtures (λ>2) the emissions are extremely low, but they show and increase when approaching to the stoichiometric condition, reaching a maximum for λ=1.3, which is considered the critical limit [10]. In order to obtain extremely low emissions, it is necessary to keep the equivalence ratio higher than this critical value. If this condition is satisfied, there is not even the need for an aftertreatment system. However, at these conditions the maximum power output achievable is only about 50% of that of a gasoline engine operating at stoichiometric, thus making it necessary to use turbocharging in order to achieve acceptable values of power output [11], as it is displayed in Figure 3.4. Combining turbocharging with constant lean mixture allows the engine to reach the 80% of the power output of said gasoline engine. The employment of a lean mixture increases the engine efficiency, which has a peak at λ=3.3. the choice of the equivalence ratio to be used needs to be a compromise between efficiency and power outputs, while always meeting the emissions standards.

It is possible to run a PFI-H_2ICE at stoichiometric conditions with the aim of limiting the power loss in comparison with a traditional engine. However, it is clear that in this case the engine needs an aftertreatment system. The engine displays higher power outputs, but on the other hand combustion anomalies are most likely to occur.

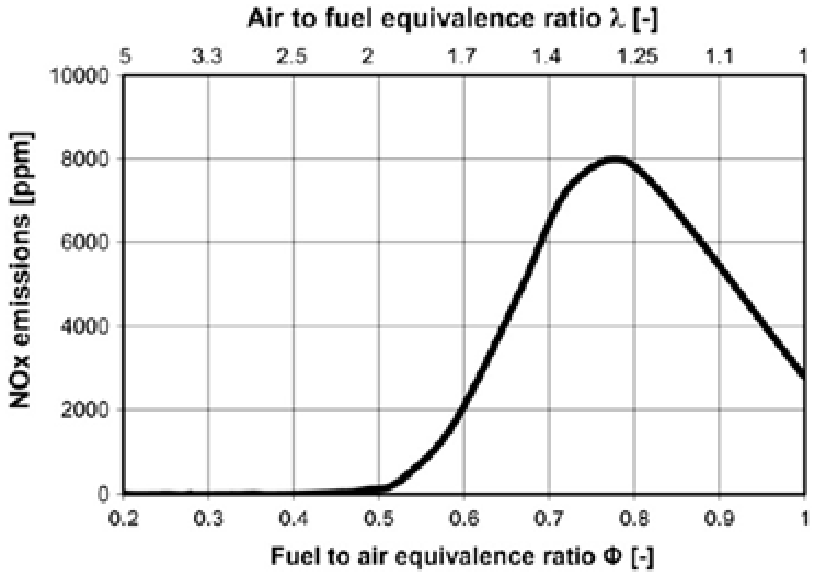

Figure 3.3: Correlation of air–fuel ratio and NO_x emissions for homogeneous operation [10].

It is also possible to combine lean-burn and stoichiometric operations. More specifically, using variable lean air-fuel ratios at low loads, thus achieving good values of efficiency and extremely low emissions. Once a certain power demand is exceeded, the engine switches to stoichiometric operating mode. In this way, the critical operating range ($1<\lambda<2$) is avoided, and the engine can be equipped with a conventional aftertreatment system [11].

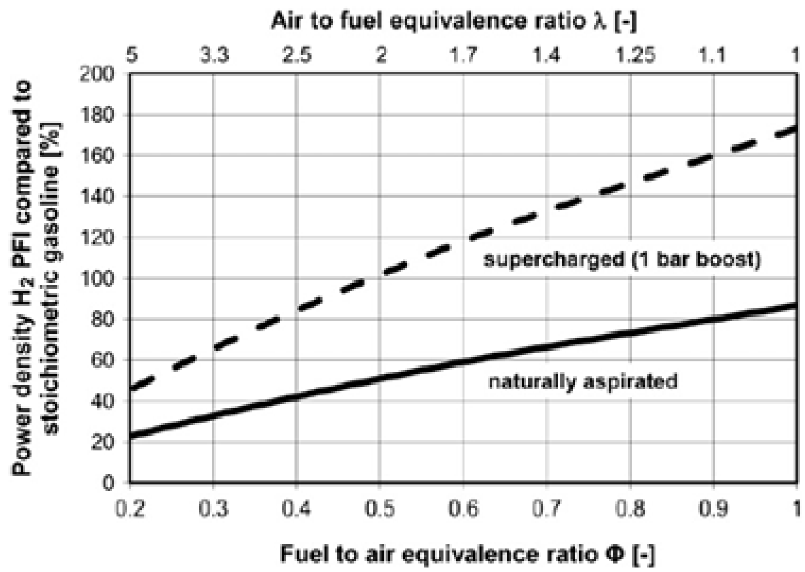

Figure 3.4: Theoretical power density of a PFI H_2 engine compared to stoichiometric gasoline operation as a function of equivalence ratio and charging strategy [11].

3.2 Direct injection H_2ICE

The development of direct injection H_2ICEs was dictated by the need to avoid combustion anomalies and to increase the power output of the engine while still achieving almost-zero emissions. Nowadays, this technology is the most attractive among all the advanced options in the field of H_2ICEs especially for its high volumetric efficiency and its capability to avoid preignition. The high volumetric efficiency is due to the fact that the fuel is injected in the combustion chamber when the intake valves are already closed. In this way, the displacement of fresh charge through the intake ports is avoided, thus obtaining a higher amount of fresh charge in the cylinder compared to that of an indirect injection engine. In fact, when hydrogen is injected in the chamber, it does not push the fresh air, previously trapped, out. Therefore, in comparison with a PFI engine, at the same load, or at the same IMEP, a leaner mixture can be obtained, meaning a higher efficiency and lower NO_x emissions can be reached. The upper limit of the mean effective pressure achievable by a PFI engine is, in fact, determined, by the inevitable displacement of air through the intake ports which takes place at the time of the injection. As it can be appreciated in Figure 3.5, said higher volumetric efficiency, together with the higher heat of combustion of hydrogen, enables DI-H_2ICEs to reach a power density approximately 115% that of an identical engine operated with gasoline.

In order to avoid preignition, it is necessary to minimize the residence time that the mixture is exposed to hotspots that could possibly ignite it and to improve the mixing of the mixture. To achieve this, it is sufficient to operate on the injection timing. The injection timing has, in fact, a great influence on the mixture homogenization and therefore on the combustion characteristics. The amount of hydrogen injected in the combustion chamber becomes independent from the pressure inside the chamber itself only if critical conditions inside the injector

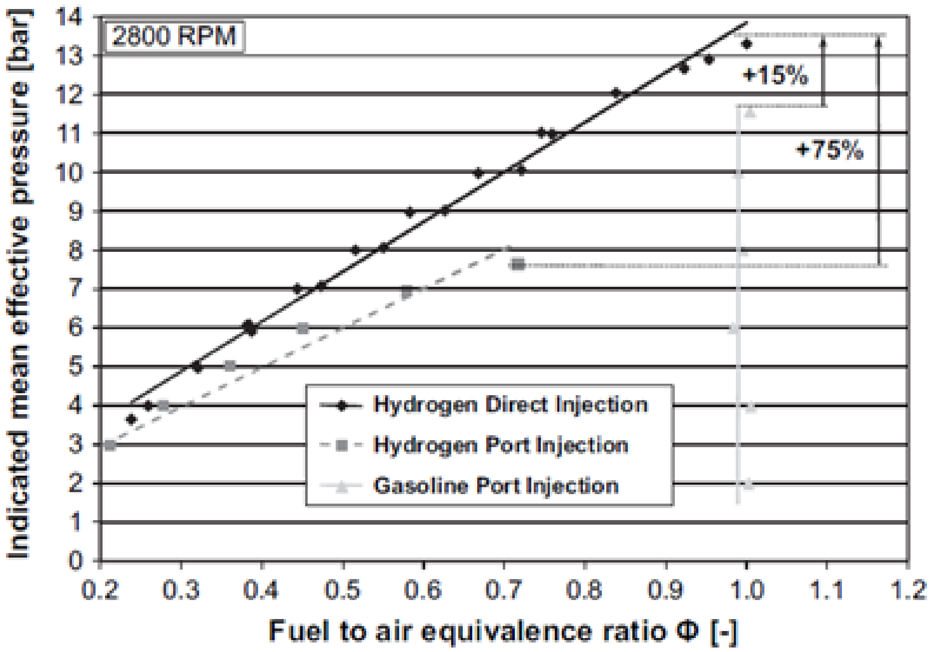

Figure 3.5: Indicated mean effective pressure comparison for gasoline and hydrogen port injection as well as hydrogen DI operation [12].

nozzle are met. A choked flow in the nozzle is achieved when the ratio between the pressure inside the injector and the pressure inside the chamber is of about 0.53. Therefore, the injection pressure needs to be more than double of that of the combustion chamber, meaning that the pressure required for the injector depends on the strategy chosen: an early DI requires injection pressures of about 5-20 bar, while a late DI requires up to 100-300 bar. This is critical for hydrogen engine calibration and also for an accurate fuel metering. Earlier the injection, more time is available for the mixture to reach a homogeneous composition, in other words air and hydrogen have more time to mix together. On the contrary, when a late injection is used, the mixture only has a limited time to properly mix, thus resulting in a stratified charge at spark time. Despite the importance of injection timing in regard to NO_x emissions, its impact is highly dependent on both the engine load and the overall equivalence ratio. Tests carried out on a single-cylinder research engine clearly show the NO_x emissions results, for various equivalence ratios, at 2000 rpm, as a function of the SOI. These results are shown in Figure 3.6. Since the engine is operated without throttling, the equivalence ratio is equivalent to the engine load. Extremely low NO_x emissions are obtained at low loads, employing an early injection, because at ignition timing the mixture results to be homogeneous. At the same load, by delaying the SOI, the mixture results to be stratified, with both hydrogen-rich zones and very lean ones. Even though the overall equivalence ratio is lean, a significant increase in the NO_x emissions can be seen, as a result of the combustion of said hydrogen-rich zones. On the other hand, for high engine loads, this trend is opposite. In fact, with an early injection the resulting mixture is homogeneous and very close to the stoichiometric limit, thus producing high levels of NO_x emissions. On the contrary, employing a late injection results in a stratified mixture with rich zones that are even richer than stoichiometric which, however, reduces the overall NO_x emissions. This happens because the critical equivalence ratio regime (λ=1.3) is avoided.

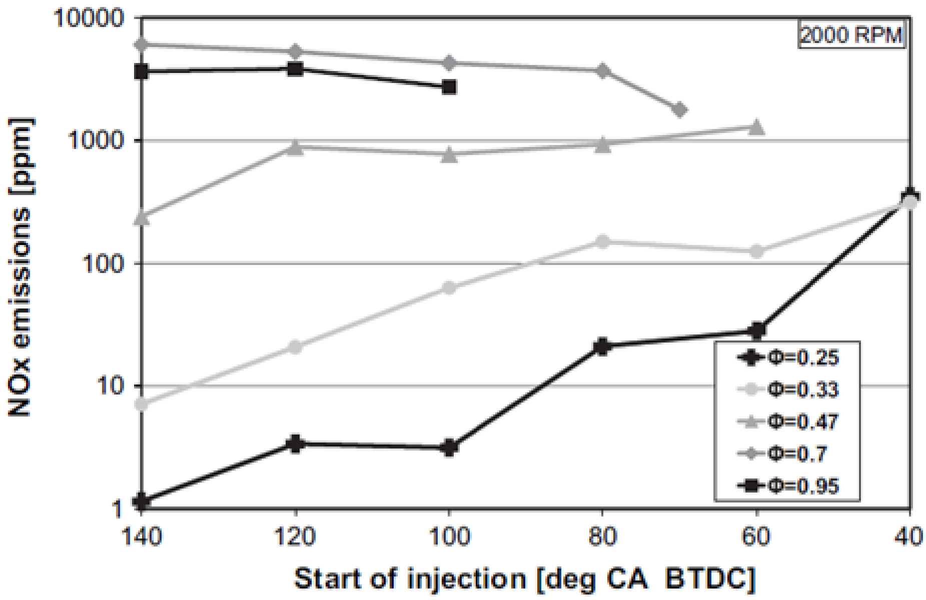

Figure 3.6: Typical NO_x emissions pattern for H_2 DI operation [13].

From these results it appears clear that, although engine efficiency improvements at all loads are achieved through direct injections, there is a trade-off between said efficiency and NO_x emissions. To address this issue, it has been demonstrated that multiple injections are an effective tool. In fact, the results of the tests carried out on the same single-cylinder research engine show a significative reduction in NO_x emissions while still achieving good levels of engine efficiency. In the Figure 3.7, a scheme of different injection strategies and their timing is shown. However, multi-injection strategy still poses some challenges for the injection system in terms of pressure levels and flow rates. These challenges are mainly due to the short time available for the injection during the combustion phase. Overall, the requirements of a hydrogen injector are: hydrogen pressure up to 300 bar while the injector tip heats up to 300-400°C, a metering accuracy of 2%, a minimum injection duration of 0.1 ms and leakage rates of less than 0.1% of the full flow [11].

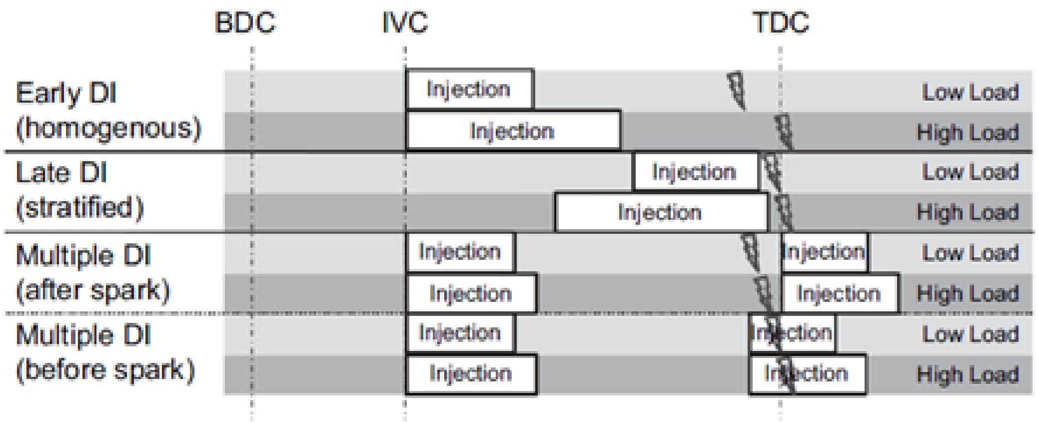

Figure 3.7: Schematic of injection strategies for H_2 DI [14].

Chapter 4

Pre-chamber combustion system

The engine in object relies on an unconventional combustion system that has been recently developed by Italtecnica Srl and is undergoing patent approval. Pre-chamber ignition is a quite long-known technology, mainly used in large engines in which its main benefits are better appreciable. These said benefits are ignition in multiple sites to fully and quickly burn the large cylinder volume and higher ignition energy to ignite very diluted mixtures. The main features of said system are the presence of a pre-chamber in addition to the main combustion chamber and the fact that the engine is operated with a leaner mixture. The latter allows the engine to work at higher thermal efficiency and the emissions of pollutants to be lower, especially those of oxides of nitrogen and carbon monoxide. The combustion is started in the pre-chamber and the partially oxidated products of said combustion, through a dedicated passage, flow into the main chamber where they ignite the leaner mixture inside of it.

This combustion system has been first studied and proposed during the 60's by the Russian scientist L. A. Gussak. There are other examples in the state of the art of the use of a pre-chamber in gasoline, diesel or gas engines, such as patents US 8925518 B1, US 20120103302 A1 and US 20160053668 A1. The main differences among these are basically on the number and the position of fuel injectors and spark plugs. On the other hand, all these inventions present some issues that have slowed down the development of said technologies, in particular because of reliability problems and unsatisfying results in terms of reduction of pollutants emissions. The reliability issues consist on the overheating of parts of the pre-chamber and the formation of carbon deposits on the pre-chamber walls, the electrodes of the spark plugs and the outlets of the pre-chamber. Furthermore, the reduction of pollutants produced was not enough to avoid the use of aftertreatment systems, such as reduction catalysts and anti-particulate filters. Also, the rich mixture in the pre-chamber caused a very stratified charge, hence a transition from lean to rich that led to higher NO_X emissions. Moreover, with said traditional pre-chamber devices the mixture in the pre-chamber resulted in a rich and stratified one. This transition from a rich to a lean mixture caused an increase in the emissions of NO_X.

This pre-chamber combustion system can be employed either in an active or a passive mode based on the fact that in the pre-chamber there is a fuel injector or not. The overall interest towards this technical solution has been growing during the recent years following its implementation in highly supercharged Formula-1 engines. These engines display a passive pre-chamber system since they are under no emission regulations and therefore, they can be operated with an air-to-fuel ratio easy to achieve but that would cause too high levels of emissions for a passenger car [15].

4.1 Passive pre-chamber

A passive pre-chamber system works in a slightly different way, meaning that there is not any fuel or air directly injected into the pre-chamber. A small fraction of stoichiometric mixture flows from the main chamber to the pre-chamber at the beginning of the compression stroke, where it is ignited by the spark plug. Thanks to the pressure rising, the combustion products are then sprayed, by means of the orifices, back to the main chamber where they kick off the main combustion by igniting the mixture in multiple ignition sites.

As it can be seen in the graph in Figure 4.1, a SI engine efficiency increases along with its compression ratio. However, after a certain point this increase in compression ratio reaches a limit because knock tendencies, and therefore the degradation of the combustion, start to become important. To minimize this danger, a measure could be that of retarding the combustion that, however, results in a decrease in efficiency. Another possible solution is to reduce the time for pre-reactions in the unburned mixture. To do so the combustion has to be accelerated, for example by increasing turbulence in the main combustion chamber or by igniting a large volume fraction of the mixture. The latter can be easily achieved through a passive pre-chamber system. Due to the usage of a pre-chamber, the advantage in knock behavior at full load can be used to work with a higher compression ratio. The latter is chosen so that at full load fuel consumption is the same as it is with a spark plug. The higher compression ratio results in a better fuel consumption throughout the WLTP cycle [15].

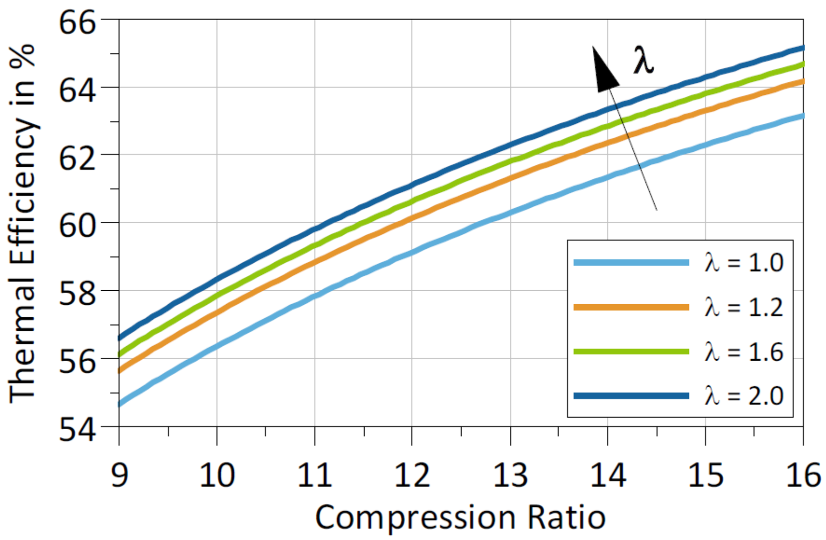

Figure 4.1: Thermal efficiency dependency on the compression ratio and the air-to-fuel ratio [15].

A high engine efficiency is made reachable by lean-burn operation. In fact, the higher dilution, the higher achievable efficiency. Moreover, the reduction in wall heat losses also contributes to it. The dilution is limited by the laminar flame velocity, that after a certain point falls significantly, resulting in longer fuel conversion periods, low efficiencies, and even the risk of quenching. The use of a pre-chamber is a huge advantage in this optic. In fact, as shown in Figure 4.2, the flame jets which from the pre-chamber flow into the main combustion chamber introduce into it a much greater ignition energy than that introduced by a simple spark plug. Furthermore, by doing so, the ignition locations are multiple and spread all over the combustion chamber, resulting in a shorter rate of conversion. Hence, a passive pre-chamber ignition system allows without any problems the ignition of lean mixtures. However, the combustion has to start inside the pre-chamber, and it needs to be started by a spark plug in a lean state and then there are the same problems of a main combustion spark plug. In fact, as the air/fuel ratio rises, the intensity of heat release is reduced in the pre-chamber, making it hard to possibly achieve any benefit from a two-stage ignition process. In order to tackle this issue, research is taking place to find the right position of the injector, in combination with an appropriate multiple-injection strategy. The goal is to force the richer mixture in the pre-chamber, while ensuring a better ignition condition, independently from the main chamber mixture.

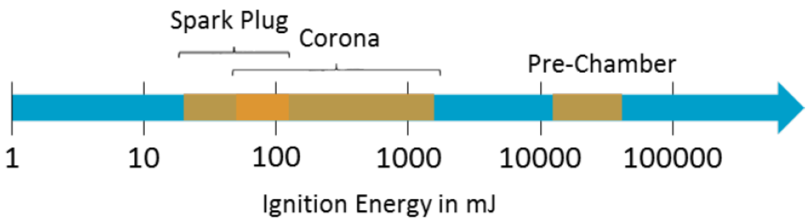

Figure 4.2: Ignition energy compared for different ignition systems [15].

4.2 Active pre-chamber

An active pre-chamber combustion system requires a pre-chamber for each cylinder, a dedicated fuel delivery system, a spark plug, and an injector inside the pre-chamber itself. Furthermore, another injector can be employed inside the pre-chamber to add to the charge exhaust gases or an inert gas for reducing the combustion temperature, leading to lower NO_X emissions, and for scavenging purposes. In this case, some fuel is injected in the pre-chamber to obtain a rich mixture, while in the main chamber there is a lean one. Thanks to the spark plug inside of it, the combustion starts and develops quickly inside the pre-chamber and the products flow through some orifices into the main chamber, where the main combustion then takes place.

Unlike a passive pre-chamber system, it allows the engine to achieve completely different air-to-fuel ratios between the pre-chamber and the main chamber. In this way, a significant dilution of the homogeneous mixture can be achieved, leading to higher efficiencies and increasingly lower levels of NO_X, as it can be appreciated in Figure 4.3. A further level of dilution in order to increase the efficiency can be reached through exhaust gas recirculation (EGR), depending on the load point this can be achieved by means of internally or externally recirculated exhaust gases. In both cases, either with air or with exhaust gases, any further increase in dilution is limited by an excessively slow flame propagation.

An active pre-chamber combustion helps to improve low-load and cold-starting capabilities [15]. The main drawback of an active pre-chamber system is its high costs of production: injectors in the pre-chamber need to have very small holes, and a dedicated fuel delivery system is required.

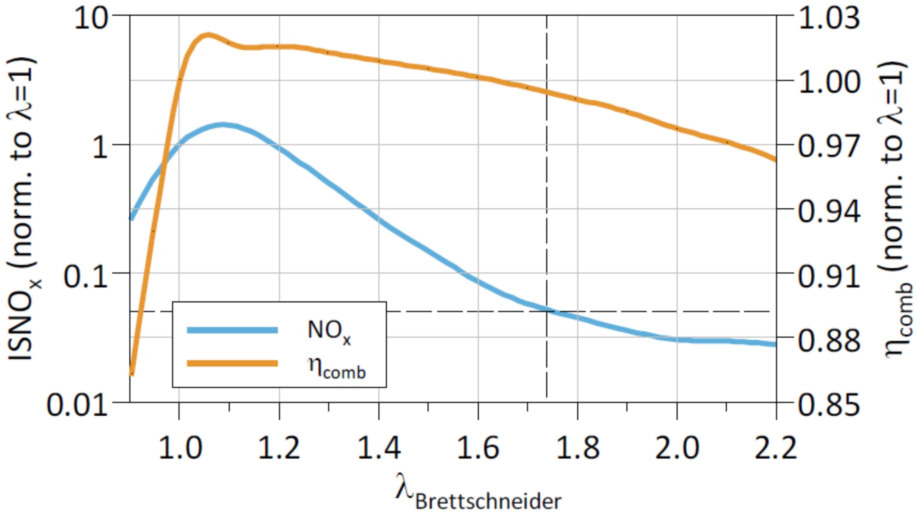

Figure 4.3: Specific NO_X emissions and combustion efficiency vs λ, normalized to $\lambda = 1$ [15].

Another possible and interesting solution is the combination of both active and passive combustion processes, combining their advantages. To do so, a map of operating modes needs to be produced, meaning that in specific ranges the pre-chamber will be operated passively while in others it will be operated actively. The ultimate goal is to find a pre-chamber layout that works with both modes throughout the entire operating map, that works adequately even at low loads close to idling, and that gives the greatest potential reduction of fuel consumption [15].

4.3 Italtecnica's innovative pre-chamber system

The main cause of all these issues in the existing examples of pre-chamber devices can be found simply in the position of the spark plug inside the pre-chamber itself. More specifically, the spark plug placed in the upper portion of the pre-chamber. Hence, to tackle all these problems at once, the position of the spark plug inside the pre-chamber is what needs to be reconsidered and it is the actual innovation about this invention. As it can be seen in Figures 4.4 and 4.5, the spark plug (13) is placed in an advanced position with respect to the injectors (14 and 15). In this way, the electrodes of the spark plug (13a and 13b) are in close proximity with the orifices (11) that connect the pre-chamber with the main one. This arrangement allows the ejection of the combustion products and the free radicals into the main chamber, while also preventing the leakage of unburned liquid fuel. In fact, the lower is the distance between the electrodes and the orifices, more are the benefits coming from this placing. In order to place the spark plug even closer to the orifices and therefore to optimizes its previously mentioned effects, it can be made up of the only central electrode while the side electrode can be constituted of a conductive material bar placed directly inside the pre-chamber. Furthermore, the injector is placed in such a way that the fuel is injected directly on the electrodes of the spark plug or at least in their direction. When the fuel jet hits the central electrode, it atomizes and vaporizes more quickly than it does in the traditional injection. Another reason for which the fuel is injected on the electrode is to refrigerate it in order to avoid overheating.

In addition, in the Figures 4.4 and 4.5 it can be seen that inside the pre-chamber, apart from the spark plug, there are also two injectors. One of the two (14) is a fuel injector, used in the event of the active operation of the pre-chamber. The other one (15) is an additional injector, used to inject inside the pre-chamber either exhaust gases or an inert gas (such as nytrogen or carbon dioxide) or liquid (such as water). This additional injection has two main goals: the first is to decrease the combustion temperature in order to also decrease the NO_X emissions, and the second is to obtain the scavenging of the pre-chamber and the cleaning of the spark plug and the injectors in order to reduce the formation of carbon residues. Hence, said carbon residues can be in large part avoided by this injection of inert gas or liquid or exhaust gases. Just like the fuel injector, also this additional injector is to be controlled by the ECU for what concerns the injection timing and phase. Said injection can take place either during the intake phase or during the compression one. The amount of the inert gas/liquid injected should account for the 10-40% of the total mass of the mixture and its pressure is to be controlled by a pressure regulator.

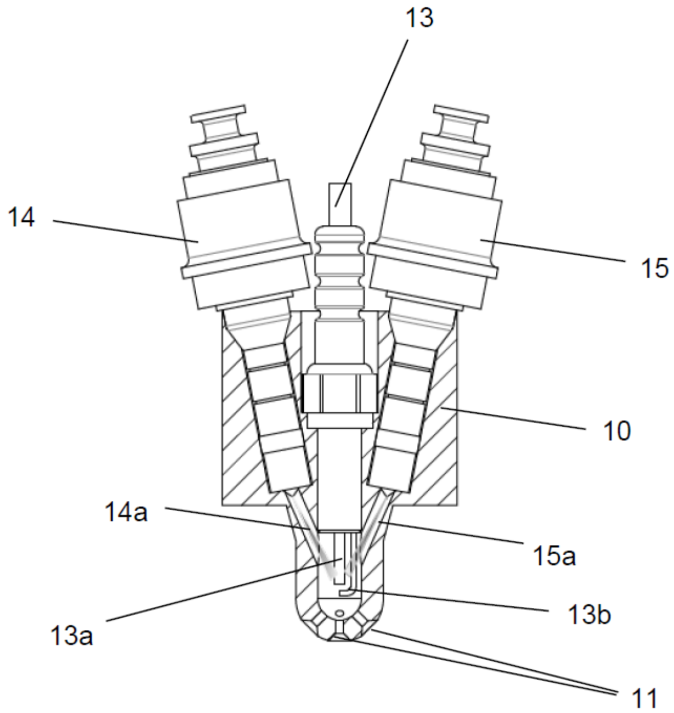

Figure 4.4: Pre-chamber assembly - front view.

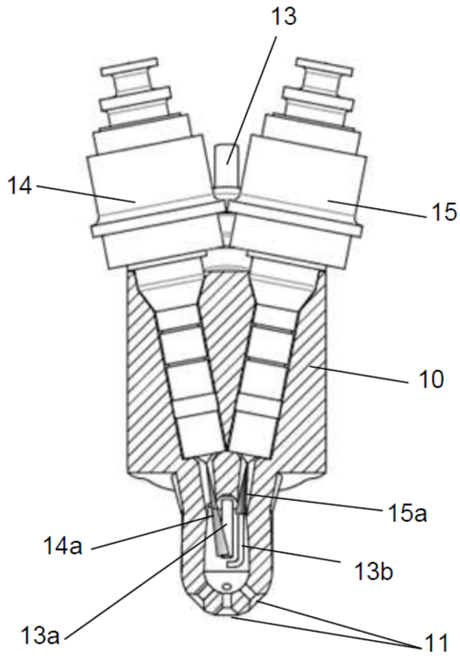

Figure 4.5: Pre-chamber assembly - side view.

In Figure 4.6 a scheme of the thermodynamic cycle is represented, where the different phases can be appreciated. During the intake phase (a) the additional injection (i) usually takes place and its duration, as it was said, depends on the quantity of mixture inside the pre-chamber. During the compression phase (c) the injection of the fuel inside the pre-chamber takes place. Said injection can be either single or split into multiple injections, indicated in the figure as I_1, I_2, I_3, I_4. The next phases are the expansion one (e) and the exhaust one (s). The spark time is marked in the figure with the number 3.

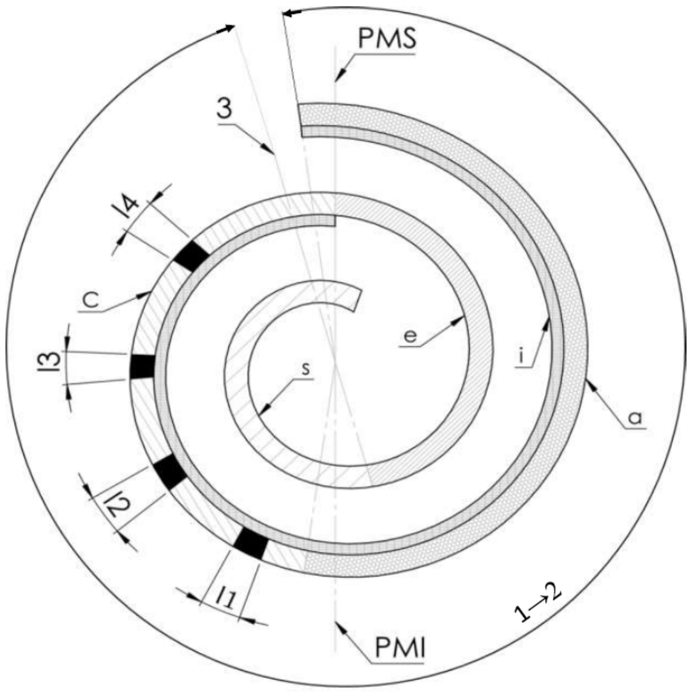

Figure 4.6: Schematic view of the thermodynamic cycle.

Moreover, the pre-combustion system hereby described can be fueled either by a premixed mixture or by just fuel. In Figure 4.7 there is a schematic diagram of a system fueled by a mixture of fuel and air. Apart from the common elements which are present in both the two possible designs, such as the pre-chamber itself, the spark plugs and the injector, it is interesting to analyze the other devices necessary to make the system work. The fuel is stored in a tank (18), and it is released by a feed pump (19) into the fueling system. If the pre-chamber and the main combustion chamber are fueled with the same fuel there is only a tank (18), otherwise there can be two different ones. Same thing for the feed pump, that in this case fuels both the injector (26) and the main chamber. There is a pressure regulator (21a) that controls the fuel pressure before it gets to the injector (22). The fuel injected by the latter mixes with previously filtered air, that comes from an air intake (23a) and is suctioned by a compressor (23) downstream of the injector. Downstream of the latter there is a flowmeter that measures the quantity of air inside the system and sends a signal to the ECU, which in response regulates the injector (22). Hence, inside a smaller tank (25) a mixture with the desired air-to-fuel ratio is formed and another pressure regulator (21b) ensures a constant value of pressure upstream of the injector (14).

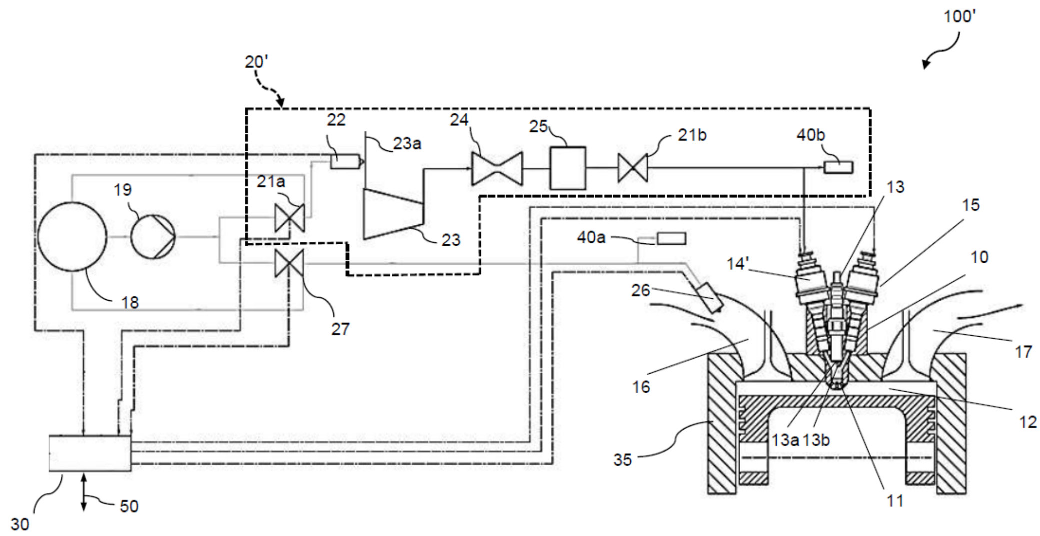

Figure 4.7: Schematic diagram of a system fueled by air-fuel mixture.

On the other hand, in Figure 4.8 there is a schematic diagram of an alternative system that is fueled only by pure fuel, such as gasoline, natural gas, or hydrogen. The main difference between this and the previously described system lies in the dedicated fueling system (20”) that, in this case, is much simpler. There is a pressure regulator (21a) that controls the amount of fuel coming from the tank (18) through the feed pump (19) before it gets to both the injector in the pre-chamber and the one in the intake manifold. If the system is fueled by hydrogen or natural gas, a specific high-pressure tank and an additional pressure reducer, not shown in the figure, will be needed.

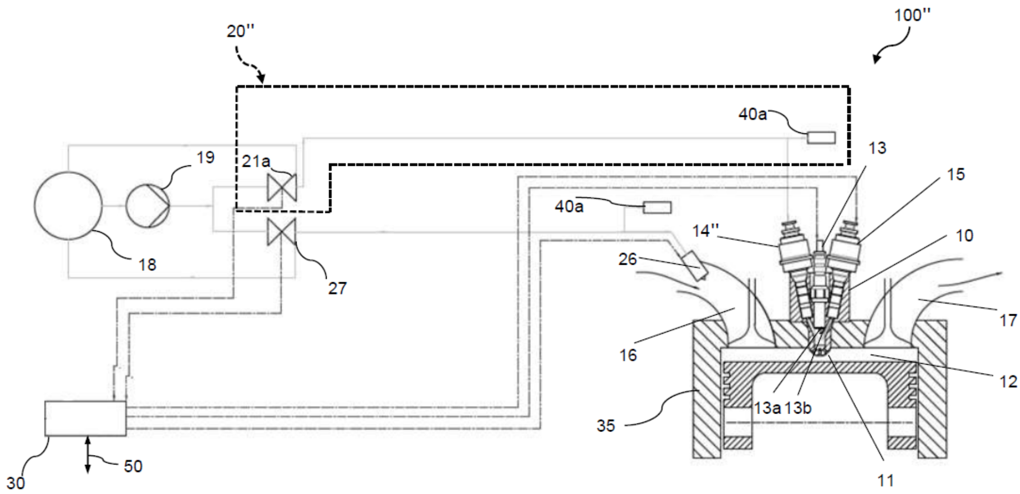

Figure 4.8: Schematic diagram of a system fueled by pure fuel.

In Figure 4.9 also the fueling system for the additional injector is described. As it was previously mentioned, this additional injector is designed to inject into the pre-chamber either exhaust gas coming from the exhaust manifold or an inert gas or liquid. Said inert substance is stored in a tank (118), a feed pump (119) delivers it to the injector (15) through a pressure regulator (121).

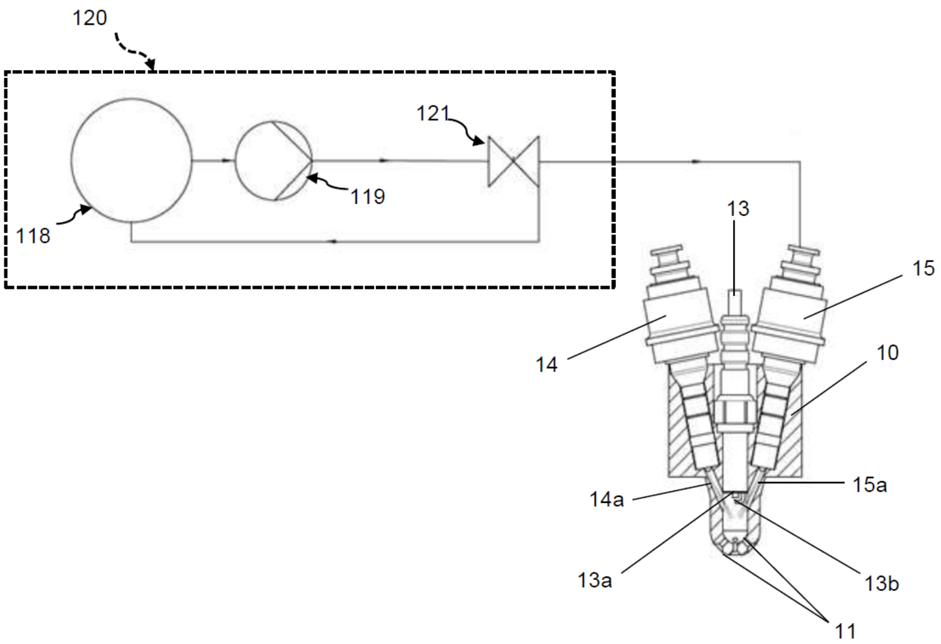

Figure 4.9: Schematic diagram of the fuel system for the additional pre-chamber injector.

The air-to-fuel ratio α injected inside the pre-chamber will be lower than the stoichiometric ratio α_0 and also lower than the air-to-fuel ratio of the mixture inside the main combustion chamber. Said ratio will be in the range of 4-12, therefore resulting in a rich mixture. The latter will go towards a very quick combustion and will result in a significant production of partially oxidated products and free radicals, which will later activate the combustion in the main chamber. On the other hand, the mixture formed inside the intake manifold will be much poorer, with an air/fuel ratio in the range of 14.7-40. A poor mixture allows to obtain benefits such as the reduction of the emission of pollutants (especially NO_X and HC), the increase of thermodynamic efficiency of the engine, and the reduction in CO_2 emissions.

Chapter 5

Current regulation and future developments

In order to establish the right field of application of this technology, it is necessary to analyze the current regulations for what concerns gasoline engines in Europe. More importantly, it is necessary to understand where the European emission control scenario is moving. This is important in order to define the right after-treatment solution to meet compliance. For this reason it is interesting to understand what is coming our way with the upcoming Euro 7 regulation. In this optic, it follows an overview on the weak spots of the current Euro 6 regulation, and the consequent additions that would make it more effective in the scope of reaching the goals set by the Commission and also less complex for the car manufacturers.

5.1 Euro 6 and its issues

In 1992 the European Commission gave start to a European pathway for vehicle emissions control, starting with the first regulation, the so-called Euro 1. In 2005 the Commission adopted the Thematic Strategy on Air Pollution, with the aim to reduce transportation emissions as part of an overall air-quality-improvement strategy. Up until now this pathway has consisted of six stages of increasingly stringent emission control requirements, the last step of which, Euro 6, came into force in 2015.

This last regulation has been among all the one that required the greatest emission reductions of all the previous stages. In particular, the light.duty standards include more stringent NO_X limits for diesel vehicles and new particle number limit for gasoline direct injection engines [16]. Euro 6 regulation contains all the requirements that a vehicle musts comply with in order to receive a European Commission type-approval. For each fuel it is specified which tests a vehicle propelled with such fuel needs to be subjected to. Said tests are shown in Table 5.1.

Vehicle category	Vehicles with positive ignition engines including hybrids (1) (2)								Vehicles with compression ignition engines including hybrids	Pure electric vehicles	Hydrogen fuel cell vehicles
	Mono fuel				Bi-fuel (3)			Flex-fuel (3)			
Reference fuel	Petrol (E10)	LPG	NG/Biome-thane	Hydrogen (ICE)	Petrol (E10) / LPG	Petrol (E10) / NG/Biome-thane	Petrol (E10) / Hydrogen (ICE) (4)	Petrol (E10) / Ethanol (E85)	Diesel (B7)	—	Hydrogen (Fuel Cell)
Gaseous pollutants (Type 1 test)	Yes	Yes	Yes	Yes (4)	Yes (both fuels)	Yes (both fuels)	Yes (both fuels)	Yes (both fuels)	Yes	—	—
PM (Type 1 test)	Yes	—	—	—	Yes (petrol only)	Yes (petrol only)	Yes (petrol only)	Yes (both fuels)	Yes	—	—
PN	Yes	—	—	—	Yes (petrol only)	Yes (petrol only)	Yes (petrol only)	Yes (both fuels)	Yes	—	—
Gaseous pollutants, RDE (Type 1A test)	Yes	Yes	Yes	Yes (4)	Yes (both fuels)	Yes (both fuels)	Yes (both fuels)	Yes (both fuels)	Yes	—	—
PN, RDE (Type 1A test) (5)	Yes	—	—	—	Yes (petrol only)	Yes (petrol only)	Yes (petrol only)	Yes (both fuels)	Yes	—	—
ATCT (14 °C test)	Yes	Yes	Yes	Yes (4)	Yes (both fuels)	Yes (both fuels)	Yes (both fuels)	Yes (both fuels)	Yes	—	—

Table 5.1: Application of test requirements for type-approval and extensions [17].

Data from real driving conditions measurements carried on hundreds of thousands of light-duty vehicles [18] show that the Euro standards have been ineffective in their scope to reduce, especially, the real-world NO_X emissions from diesel vehicles. While the nominal NO_X limits for diesel vehicles have gone down by 84% from Euro 3 to Euro 6, their actual emissions have reduced by only 32% [19]. The gap between nominal NO_X limits and real-world emissions, and their decrease from Euro 3 to Euro 6 can be seen in Figure 5.1.

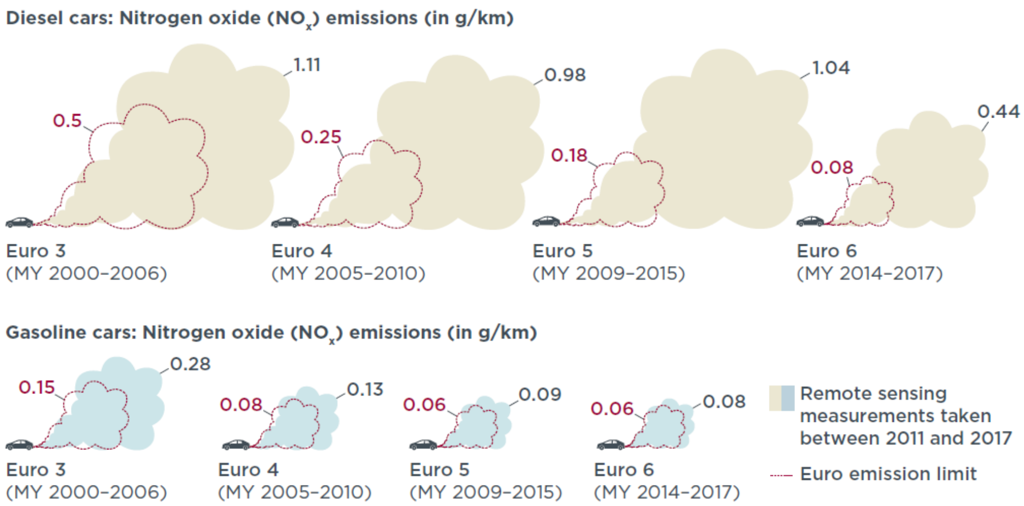

Figure 5.1: Nitrogen oxide (NO_X) emissions (in g/km) estimated via remote sensing of the on-road fleet, from Euro 3 to Euro 6, for EU passenger vehicles [20].

The emission limits of the current regulation, the Euro 6, were adopted in 2015 and therefore they do not fully take advantage of the current technology potential for emission reduction. In fact, the current technologies would allow the introduction of significantly more stringent emission limits than those contained in the Euro 6.

Depending on the application and on the fuel type, there are different limits for NO_X, HC and CO. For example, while gasoline direct injection engines are subjected to PM and PN limits, port fuel injection engines are not, although they can have PN emissions above the regulatory limit set for direct injection engines. In Table 5.2 said limits are shown for light-duty vehicles, light-commercial vehicles whether they are propelled with a gasoline or a diesel engine.

	LDVs, LCVs Class 1[a]		LCVs Class 2		LCVs Class 3	
	Gasoline[b]	Diesel[c]	Gasoline	Diesel	Gasoline	Diesel
NMHC (mg/km)	68	-	90	-	108	-
THC (mg/km)	100	-	130	-	160	-
NO_x (mg/km)	60	80	75	105	82	125
THC + NO_x (mg/km)	-	170	-	195	-	215
CO (mg/km)	1,000	500	1,810	630	2,270	740
PM (mg/km)	4.5[d]	4.5	4.5[d]	4.5	4.5[d]	4.5
PN (#/km)	6×10^{11} [d]	6×10^{11}	6×10^{11} [d]	6×10^{11}	6×10^{11} [d]	6×10^{11}

Notes: [a]Classes 1 through 3 are weight classes. [b]Gasoline is used as a proxy term for positive ignition (PI) engines. [c]Diesel is used as a proxy term for compression ignition (CI) engines. [d]Applicable to direct injection engines only.

Table 5.2: Application of test requirements for type-approval and extensions [20].

Another issue with the current regulation is the fact that its emissions limits are generally lower than those set by other countries standards. Taking into consideration China's and United States' regulations, in Figure 5.2 there is a graph that show said differences. First of all, both the U.S. Tier 3 and China 6 standards are fuel neutral, and the U.S. Tier 3 is also application neutral. This means that the same limits apply both for diesel and gasoline engines and, in the U.S., for both light-duty and light commercial vehicles. What appears clear is that the current Euro 6 NO_X emission limit is much higher than those adopted by both China and the U.S. On the other hand, Europe has taken a leading role in introducing the limit on particulate number, forcing the introduction of filters on diesel engines. Chinese standards have followed this example, while in the United States such limit still does not exist.

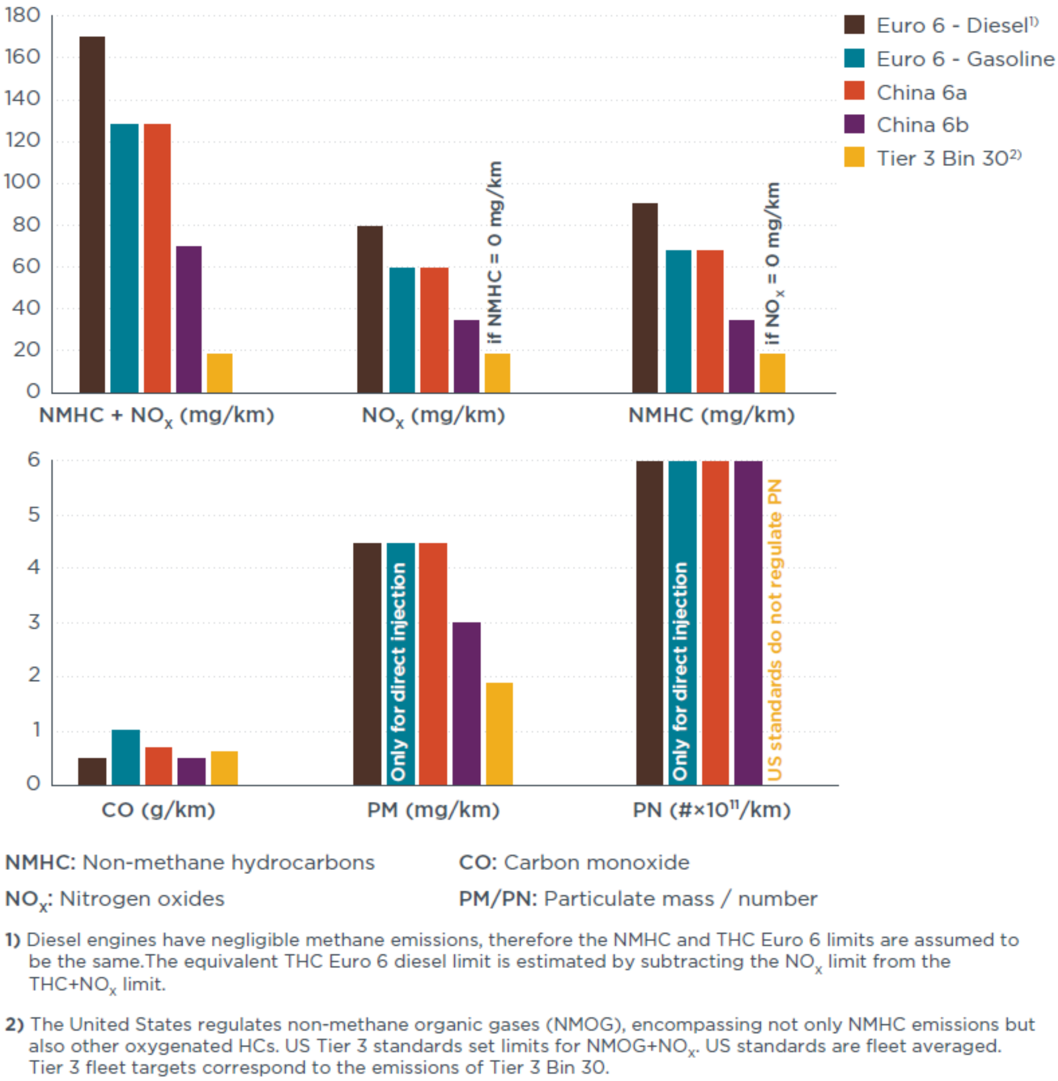

Figure 5.2: LDV emission limits according to the Euro 6, China 6, and U.S. Tier 3 standards [20].

A significant portion of PN emission is currently unregulated in Euro standards. In fact, Euro 6 excludes all volatile and semi-volatile particles, solid particles smaller than 23 nm, particles emitted by gas-powered and PFI gasoline engines and particles emitted during particulate filters regeneration. However, these unregulated particles can have a serious effect on health, both through direct exposure and because of their role in the formation of $PM_{2.5}$. The limit on PN for gasoline DI engine was introduced only in the latest Euro 6 regulation [21], but said limit was not low enough to force the introduction of gasoline particulate filters. In fact, manufacturers were able to meet the limit only by engine measures. However, in RDE tests, these engines have resulted to have much higher particulate emissions than those resulting from laboratory tests.

There are also some powerful greenhouse gases (GHGs) which are not regulated at all even though they are found in significant quantities in the exhaust gases of a motor vehicle: methane (CH_4) and nitrous oxide emissions (N_2O). Methane results from the combustion and, since it is relatively stable, catalytic converters are less effective at oxidizing it. On the contrary, N_2O forms inside the emission control systems, during the reduction of NO_X to nitrogen. While methane emissions are implicitly regulated in Euro 6, as the total HC emissions are regulated, it is not the scope of said limit to reduce CH_4 emissions, but it focuses on other, more reactive, and toxic hydrocarbons. On the other hand, N_2O are currently not regulated at all. In the United States, as part of the GHGs emission standards, both CH_4 and N_2O are regulated for all the vehicle models after 2012. In Table 5.3 there is a summary of the emissions species that are and are not currently regulated in Europe and, for the latter, it can be seen in which country, on the other hand, they are monitored.

	Emissions species	Regulated in Euro 6/VI	Regulated if not in EU
	NOx	Yes	
	THC	Yes	
	NMHC	Yes	
	CO	Yes	
	PM	Yes	
	PN >10nm	PN >23nm	
Regulated	**NH_3**	Yes-HDV No-LDV	South Korea
	CH_4	Yes-HDV No-LDV	US
	NO_2	Indirectly through NOx	US
Unregulated	Non-methane organic gases (NMOG)	Indirectly through THC	US (NMOG +NOx), South Korea (NMOG +NOx)
	N_2O	No	US, China
	Formaldehyde (CH_2O)	No	US, South Korea

Table 5.3: Emissions species investigated [22].

Currently, RDE tests are performed on public roads open to traffic, however, the regulatory provisions limit the range of driving under which the tests can take place. Initially, the intent of the regulation was to cover 95% of the full range of normal use. There are a series of boundary conditions under which the tests need to be conducted. Said boundary conditions exist for payload, altitude, cumulative altitude gain, ambient temperature, trip composition, maximum speed, and driving dynamics. Driving dynamics are quantified as follows: vehicle speed times its positive acceleration (v*a) for the upper boundary and relative positive acceleration (RPA) for the lower boundary. The dynamics boundary conditions are compared to the dynamometer cycles, such as WLTC and NEDC, in Figure 5.3. Studies on trips in real-world conditions show that the dynamic boundary conditions only cover 90% of all driving conditions in rural and highway operation, against the original 95% goal. Furthermore, to avoid potential invalid tests, RDE tests are never performed close to the dynamic boundary conditions, thus further reducing the representativeness of the test. A recent study of the European Commission [23] shows that when on-road tests are performed outside the dynamic boundary conditions they result in much higher emissions.

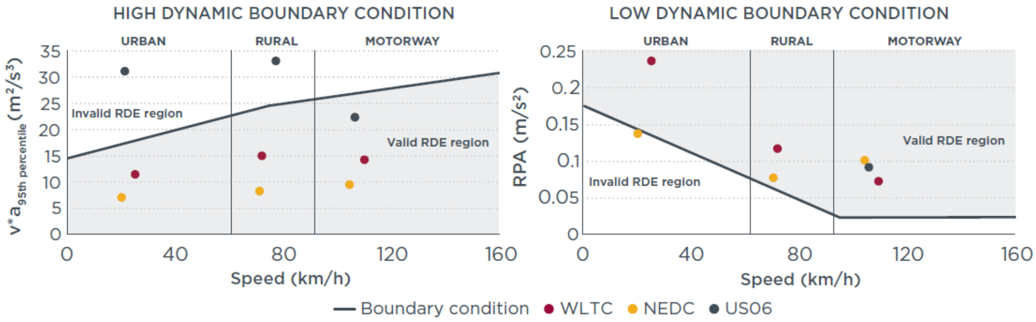

Figure 5.3: Dynamic boundary conditions compared to three dynamometer driving cycles [18].

Also, the trip composition and the associated average speeds represent an important constraint for the validity of RDE tests. Three types of operation are covered by RDE trips: urban, rural, and motorway, in this order. Because of the requirements of the trip composition, the minimum distance at the speed of a typical urban driving (around 30 km/h) is more than 20 km. RDE data from car manufacturers show that the average distance of the urban part of the test is 33 km. However, studies show that the average real-world urban trip is much shorter than that: 10-11 km driven at an average speed of 28-33 km/h. In Figure 5.4 the RDE region of validity of the urban trip compared to the typical German city trip can be seen.

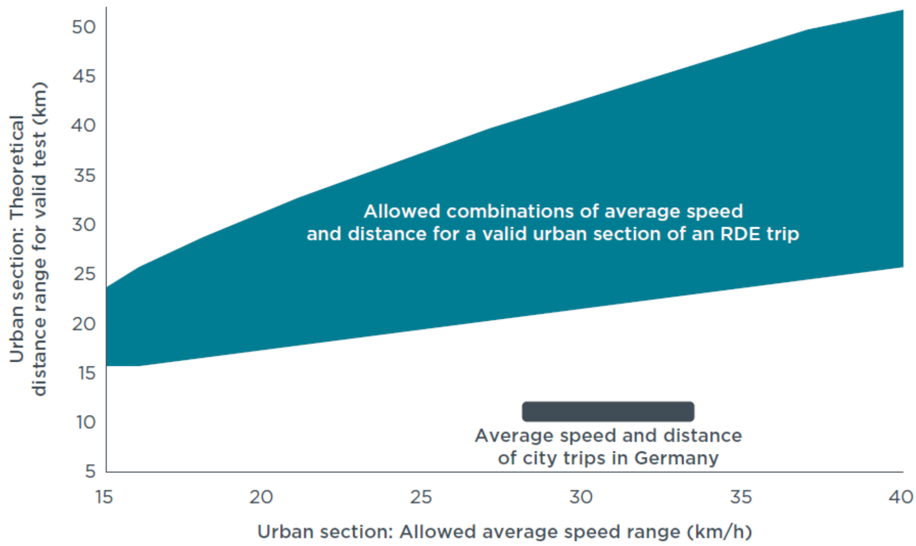

Figure 5.4: Valid RDE range of urban distance and speed versus the average German city trip [20].

These long urban trips required by the RDE provisions are responsible for the fact that the urban emission calculated through the RDE methodology is not representative of the actual emissions occurring in European cities. This is due to the fact that the most significant portion of emissions occurs during cold start: the period between the moment at which the vehicle is turned on and when the aftertreatment system reaches its operational temperature (70°C). The length of this period differs from vehicle to vehicle but generally it is limited to the first few minutes and kilometers. For this reason, a longer urban trip distance means the contribution of cold-start emissions is lower than that of real-world operations. The values measured in an RDE test are not the ones later used to determine compliance, but they are lower. In fact, raw emissions are multiplied by a corrective factor, called RDE evaluation factor. Said factor is a function of the CO_2 emissions over the RDE test and the declared CO_2 over the WLTC test; in the case of plug-in hybrids, it is also a function of the trip share driven with the engine. In

Figure 5.5 there is the graph of the function used to calculate the RDE evaluation factor. The scope of this factor is to take into account also harsher-than-usual driving conditions. However, there are already two other elements that limit the aggressive driving in the RDE regulation: dynamic boundary conditions and a trip validity check, calculated by the comparison of the RDE CO_2 with the vehicle's CO_2 characteristic curve. Therefore, this results in an actual limit that is too high and in an artificial gap between the RDE emissions reported and those actually occurring.

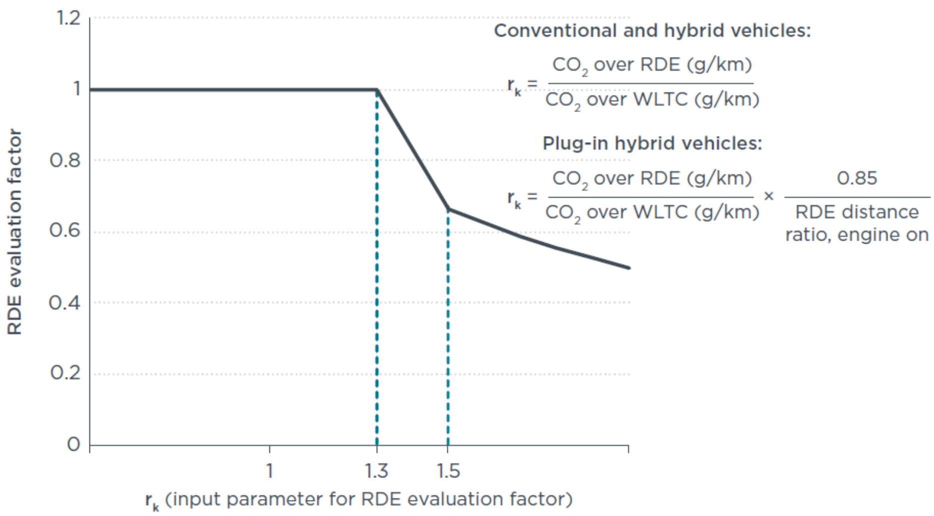

Figure 5.5: Function for calculating the RDE evaluation factor [20].

In-service conformity (ISC) testing refers to testing carried out on in-use vehicles to verify compliance with type-approval procedure. Furthermore, Euro 6 also includes minimum durability requirements, in order to guarantee the emissions performance of a vehicle over its complete lifetime. In fact, the deterioration of the emission control system can represent a significant issue for the in-use emissions of on-road vehicles. In Figure 5.6 the average CO emissions of gasoline passenger cars are shown [24]. As it can be seen, there is a quite substantial increase of CO emission with the vehicle age. Currently, Euro 6 provisions limit the ISC to 5 years or 100,000 km, whichever occurs first and define the test procedures to determine the deterioration factors, which are used to verify the durability of the emission control system up to 160,000 km. These provisions do not guarantee CO_2, fuel consumption, or electric range performance through the lifetime of the vehicle, but only cover pollutant emissions. Since the average lifetime of a EU passenger car in 2019 was 11.5 years old [25], the durability, ISC, and warranty requirements set by European regulations are not representative of the average useful life of European LDV fleet and are too limited.

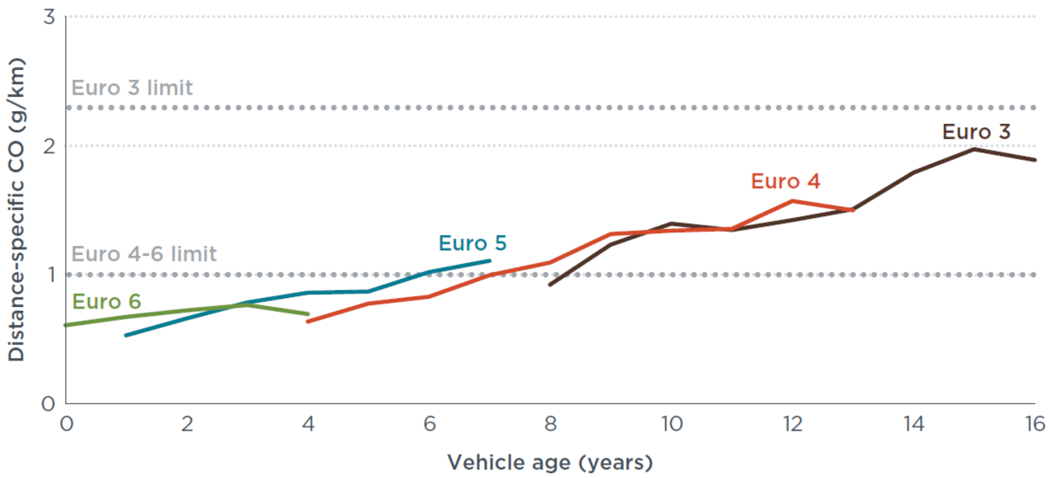

Figure 5.6: Average CO emissions as a function of vehicle age for gasoline vehicles measured with remote sensing technology [24].

Furthermore, currently an emission warranty program is not part of the regulation in the EU, meaning that manufacturers are not required to provide any warranty for vehicle emission control, to report emissions-related warranty and repair claims, or any other emissions-related defect. By comparing EU regulation to those of China and United States, it appears clear that they have in-service conformity, durability, and emissions warranty requirements that are far more extensive than the European ones. Said comparison between useful life requirements can be observed in Figure 5.7.

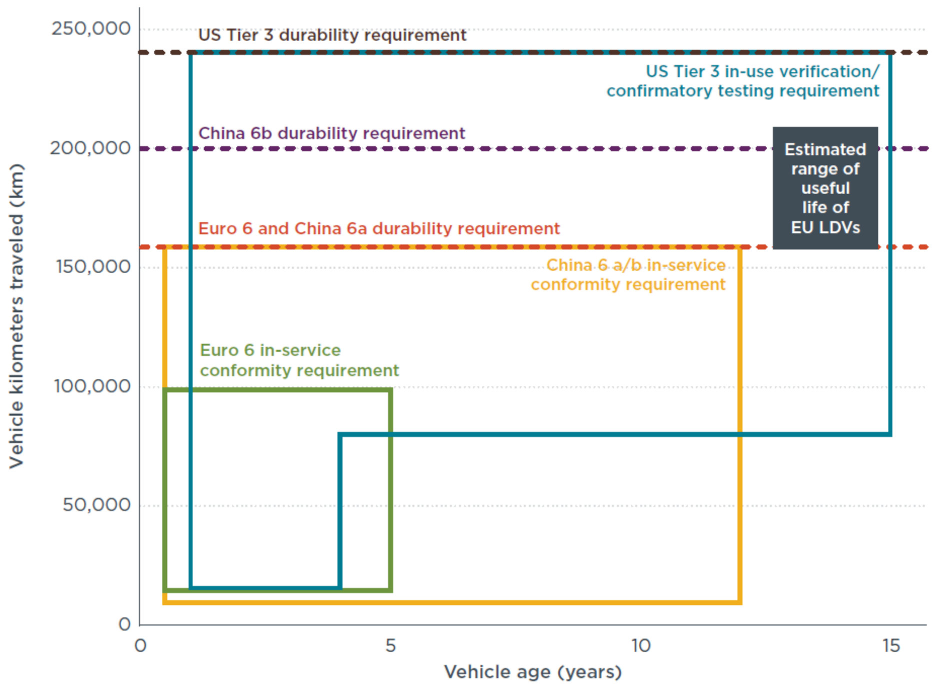

Figure 5.7: Useful life requirements for in-service conformity testing and durability demonstration in the EU, the United States, and China [20].

On-board diagnostics systems could play a fundamental role in emissions control systems, because of their ability to monitor the performance of emission control components during everyday operations and to allow the identification of malfunctions that caused higher emissions. Its effectiveness depends on which components and pollutants are monitored, the frequency of this monitoring, the definition of malfunction, and on the actions that are implemented when a malfunction is detected. European OBD program, however, is the least comprehensive among those of the other major markets. The requirements are not clearly defined and the systems do not identify malfunctions that are not explicitly listed in the regulation.

Therefore, its effectiveness is limited. For example, California and China have adopted on-board monitoring (OBM) regulations that require vehicles to collect emissions data from the vehicle's sensors. These data can be later used to improve in-use compliance.

5.2 Possible improvements

In [20] the ICCT pointed out all the flaws of the current Euro 6 regulation and what it lacks of. In the same document, they come forward with some recommendations which should guide the European Commission in the drafting of the new upcoming Euro 7 regulation.

First of all, the emission limits should become fuel-, technology-, and application-neutral and at the same time they should be tightened to more reasonable values, in relation to new technology and also to other markets, such as China and United States. More attention should be dedicated to PN emissions. In fact, by lowering the cutoff size from 23 nm to at least 10 nm, a more representative portion of particulate would be taken into account. Pollutants that are currently unregulated need to be tackled. In particular, new limits for ammonia and GHG emissions, such as N_2O and CH_4, should be introduced into the regulation.

For what concerns the RDE provisions, also in this field some changing is needed. First of all, the so-called RDE evaluation factor, used to adjust emissions downwards, should be eliminated. Also, RDE boundary conditions need to be revised. In particular, they should be extended in order to cover at least 95% of all driving conditions. RDE trip requirements should revised as well. In particular, shorter urban sections would be more representative of the actual use of cars in European cities. In this way, also the contribution to the total emissions given by cold-starts would be more representative.

For what concerns both Euro 7 and Euro VII, also the durability provisions should be revised. In particular, the useful life and the mileage requirements for durability demonstration and in-service conformity should be extended to more realistic values. Furthermore, an emission warranty program should be introduced, following the U.S. regulation.

European OBD requirements should align with those of California and China to in order to be more comprehensive and effective. Also, OBM of pollutants emissions should be introduce on top of the already existing on-board fuel consumption meters.

5.3 Euro 7

As part of the European Green Deal, the European Commission released in march 2020 an impact assessment of the upcoming Euro 7 regulation [26], in order to inform citizens and stakeholders about the current situation, problems, and possible solutions. Furthermore, both citizens and stakeholders were invited to comment on it and to give their feedback, before the Commission goes on to make the regulations. In said impact assessment, the European Commission underlined how, while Euro 6 represented an important step towards the reduction of emission, especially for the introduction of RDE testing, road transport still represents one of the main causes of air pollution in our cities. Hence, the current standards do not sufficiently contribute to the decrease of air pollution caused by road transport.

The commission identified three main issues that prevent the Euro 6 regulation from actually limiting the emissions of pollutants. First of all, the current emission standards are very complex and also contain many differences based on fuel and technology that create confusion. Its complexity requires time and resources and may lead to misinterpretations in the application of the standards. A second issue the Commission underlined is the fact that the current limits were adopted over a decade ago and therefore they no longer represent the state of the art in emission reduction technologies. Furthermore, today there are some pollutants that are of concern, while years ago they were not and therefore were not included in the regulations. Lastly, there is the need to measure real-world emissions under all conditions of use in order to prevent disproportionately high emissions. Also, air pollutants are still not monitored during the entire lifetime of vehicles, and this represents another issue the Commission wants to tackle.

Therefore, in this document the European Commission outlined both the specific and the operational objectives of the new upcoming Euro 7 regulations. The specific objective is, of course, to improve air quality in urban areas and to reduce the amount of pollutants coming form the transport sector. The operational objectives are to reduce the complexity and compliance costs, to provide appropriate and up-to-date limits for pollutant emissions, and to ensure that new vehicles keep the pollutant emissions under those limit in all conditions and throughout their entire lifetime.

There are three options the Commission sees as possible and of which it is assessing the economic, social, and environmental impacts. Option 1 provides for a narrow revision of Euro 6 and key simplifications, such as a single emissions standard for all fuels and applications, while keeping a focus on real-world testing. Option 2 involves a wider revision of Euro 6 and, in addition to the measures in option 1, more stringent limits for all vehicles: stricter limits for already-regulated pollutants, and new limits for currently unregulated pollutants. Option 3 will consider a comprehensive revision of Euro 6 and, in addition to the measures in options 2, the real-world emission monitoring over the lifetime of the vehicle.

For the development of the post-Euro 6 emission standards, the Commission receives technical advice from all the relevant expert groups working on emission legislation. All this group joined, for the occasion, an Advisory Group on Vehicle Emission Standards (AGVES). AGVES, after a period of research and study, released their preliminary findings and results in october 2020 [22]. The methodology adopted by AGVES has been first an analysis of the latest technology vehicles (Euro 6d-temp), followed by the identification of the best available technologies (BAT) as base for the future emission standards. After that, an analysis of the emission reduction potential of future emission control technologies (based on BAT) and therefore a proposal of technology scenarios for further analysis and impact assessment. The research was carried on the results of more than 500 tests over 49 LDVs. Vehicle and test data are shown in Table 5.4, where it can be seen, for each LDV, the fuel used, the type of engine, the standards to which it refers, the after-treatment system, and what kind of emission test data were available. A parallel work has been made for HDV on Euro VI.

Fuel	Vehicle data			Emission test available data	
	Engine/Powertrain	EU std	ATS (Number of vehicles)	Current RDE/Non-compliant RDE	Non-reg. pollutants
Gasoline	GDI	6d-temp	TWC+GPF (13) TWC* (1)	✓/✓	✓
	mHEV-GDI	6d/6d-temp	TWC+GPF (4)	✓/✓	
	PHEV-GDI	6d/d-temp	TWC+GPF (4)	✓/✓	✓
	PFI	6d/d-temp	TWC (5)	✓/✓	✓
	HEV-PFI	6d/d-temp	TWC (2)	✓/✓	✓
	PHEV-PFI	6d-temp	TWC (1)	✓/✓	✓
Diesel	DI	6d/d-temp	DOC+DPF+SCR (4) DOC+sDPF+ASC (1) DOC+sDPF+SCR (1) DOC+sDPF+SCR+ASC (1) LNT+DPF+SCR (3) LNT+DPF (1) DOC+DPF+2xLNT (1)	✓/✓	✓
	mHEV-DI	6d-temp	LNT+SCR+sDPF+SCR+ASC (1) DOC+SCR+SCRF (1) DOC+DPF+SCR (1)	✓/✓	✓
CNG	PFI	6d-temp	TWC (3)	✓/✓	✓
LPG	PFI	6d-temp	TWC (1)	✓/✓	

Table 5.4: Vehicle and test data included in emissions database [22].

CLOVE (Consortium for ultra Low Vehicle Emissions), a consortium of European academic, research and business experts in the field of emissions, made a proposal regarding the renovation of the current RDE, as shown in Figure 5.8. This new solution would cover conditions that are currently not controlled in RDE, therefore resulting in a wider on-road testing. Furthermore, as it can be seen, the Euro 7 limits would be technology- and fuel-neutral, and lower than the currents ones, in accordance with today's BAT.

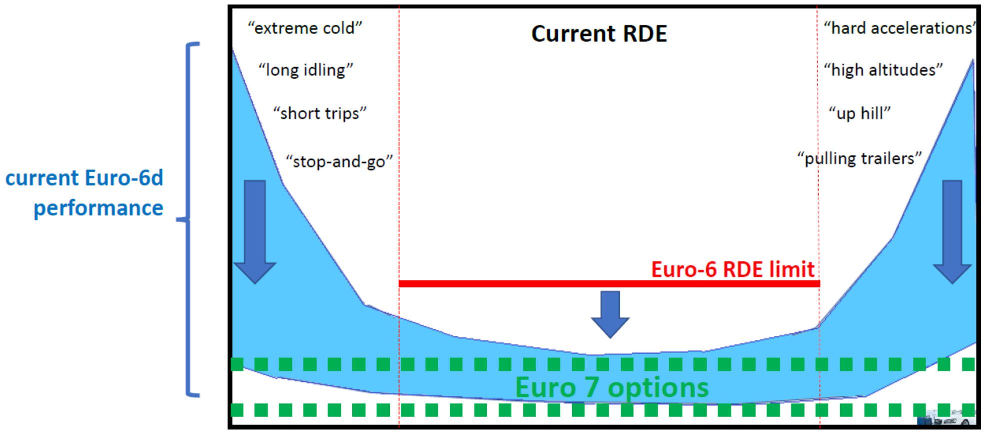

Figure 5.8: CLOVE proposal for emission limits setting [22].

Recommendations on the gasoline after-treatment technologies for Euro 7 were also made, and summarized in Figure 5.9. The different recommended possibilities can be seen: the Euro 7 baseline after-treatment system, or with the addition of the ammonia after-treatment, or with the addition of an E-cat. Also the after-treatment solution towards zero impact on the environment is shown, as the union of the other three. Furthermore, possible technologies to comply with Euro 7 scenarios were suggested. First of all, the adoption of a pre-heated catalyst, either electrical or fuel burner, and the optimisation of sizing and positioning of the after-treatment system. Also attention should be given to a high GPF filtration efficiency from clean state, an accurate combustion control, and an optimised system calibration.

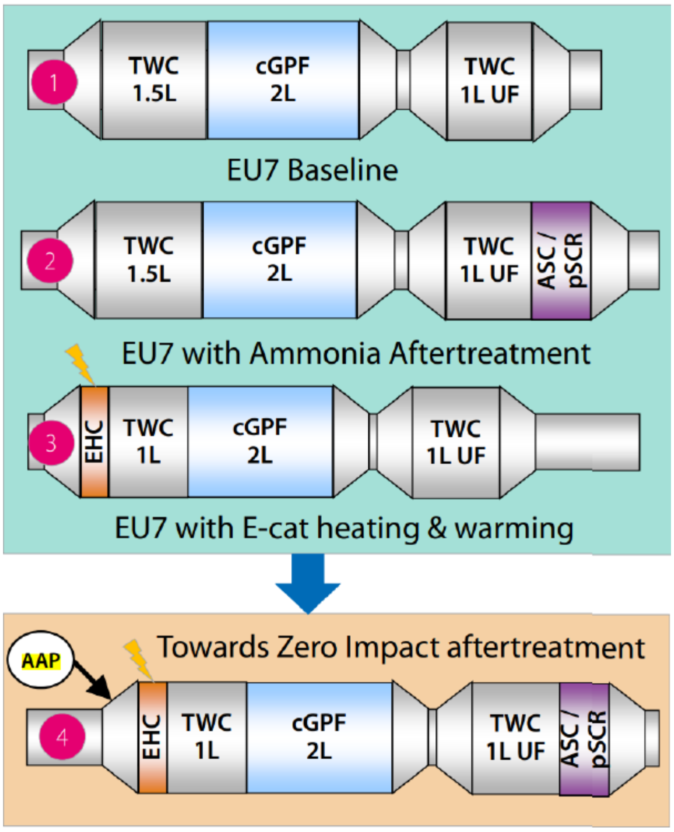

Figure 5.9: Gasoline: published views on technologies for Euro 7 [22].

Finally, in Table 5.5 and 5.6 can be seen, respectively, the proposed emission limits for LDVs in mg/km or #/km, and the proposal for the lifetime compliance. As it was anticipated, there is only one comprehensive fuel- and technology neutral limit with no conformity factors (or other correction factors) for both PCs and LCVs; also, all limits are applicable also during particle filters regeneration. Further emission limits are being discussed for what concerns NO_X, THC and NMOG/NMHC, and HCHO. Scenario A refers to the best technology known, while Scenario B refers to the application of the emission levels achieved in Scenario A for WHTC as limit in entire wide on-road range.

Euro 7 scenarios	NOx	SPN_{10}	CO	CH_4 (1)	N_2O (1)	NH_3
EURO 6	60/80 (PI/CI)	6×10^{11} (SPN_{23})	1000/500 (PI/CI)	-	-	-
A	**30**	$\mathbf{1\times10^{11}}$	**300**	**10**	**10**	**5**
B	**10**	$\mathbf{6\times10^{10}}$	**100**	**5**	**5**	**2**

Table 5.5: Euro 7 emission limits scenarios - LDV in mg/km, #/km [22].
(1) Suggested to limit weighted sum of CH_4 and N_2O instead of separate limits.

Type	Name	Regulation	Current status	Euro 7 approach
5	Durability	UNECE R83 EU 2017/1151	Whole vehicle durability Component testing in lab Deterioration factors	Whole vehicle durability, 240k km and 15 years(1) (Tier 3, US approach)

Table 5.6: Lifetime compliance LDV - proposed Euro 7 approach [22].

Chapter 6

Conclusions

From the deep research carried out on hydrogen and its supply chain, what emerged is a sector that is growing quickly: many and always more are the solutions for both its production, and its distribution and storage. Despite this, there is still a long way before hydrogen can become a major source of power for the automotive industry. Firstly, because the ways of producing it without emissions of pollutants and, therefore, without causing a further burden on the climate, are few and still too expensive. Steps ahead need to be taken in this direction: to actually be an alternative, hydrogen must be economically viable and, overall, green. Furthermore, an efficient network of distribution needs to be created. As long as there are places in Europe that cannot be properly supplied with hydrogen, this cannot become an actual alternative to traditional fuels. On the other hand, technologies to successfully use hydrogen are many and efficient, both for fuel cell vehicles and for vehicles equipped with internal combustion engines.

To fully understand the scenario in which the engine in question will enter and with which will need to comply is still too early. It is still to be seen in which direction the European Commission will move when the Euro 7 regulation will be officially drawn up. Car manufacturers, united under the European Automobile Manufacturers' Association (ACEA), have severely criticized the suggestions of regulations brought forward by the institutions that are assisting the Commission, which have been described in this work. In fact, in its position paper [27], ACEA defined the proposals presented by AGVES as technically infeasible for vehicles with combustion engines and stated that they would result almost in a ban of vehicles powered by ICEs, hybrid vehicles included. Furthermore, the new RDE test conditions suggested, namely taking into account also the worst-case driving scenarios, would result in high additional costs that all the EU citizens would have to bear. In support of this, ACEA conducted a detailed air quality study that revealed that the replacement of the oldest vehicles with new Euro 6d vehicles, together with the increasing presence of zero-emissions vehicles would show significant results, in comparison to which the most severe Euro 7 scenario would only represent a marginal benefit.

However, Euro 7 will most likely introduce more stringent and fuel- and application-neutral limits. More importance will be given to RDE testing, with additional testing conditions, and also to the monitoring of the real world emissions during the entire lifetime of vehicles. These will inevitably require a more expensive and complex after-treatment system.

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