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UNIVERSIDAD PONTIFICIA

ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

DOWNSIZING AND RIGHTSIZING OF IC ENGINES ANALYSIS IN ASPECT OF GREENHOUSE GASES EMISSION IN EUROPE

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Madrid

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Collaborating entity: ICAI – Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

INTRODUCCIÓN

Los motores de combustión interna (CI) han permitido un importante desarrollo de las actividades humanas, incluidos los automóviles que forman parte de la vida cotidiana de los seres humanos. Parte de estas actividades responsables de este desarrollo han resultado en el aumento de las emisiones de gases de efecto invernadero que producen el llamado efecto invernadero.

Esta es una de las principales preocupaciones para la sociedad actualmente y una de las posibles soluciones para reducir la contribución de los automóviles es la tendencia conocida como ‘downsizing’, ambas serán descritas por separado, se analizarán y se compararán en este proyecto.

MOTORES CI

Los motores CI se basan en la oxidación de un combustible en una cámara de combustión que utiliza esta mezcla como fluido de trabajo para el motor. Se pueden clasificar como:

- Recíproco
 - o Según el número de tiempos: Cuatro tiempos.

Consiste en un proceso dividido en cuatro eventos: carrera de admisión (las válvulas de entrada se abren y el pistón se mueve hacia abajo para absorber el fluido), la carrera de compresión (el pistón que se mueve hacia arriba comprimiendo el fluido para disminuir la temperatura de ignición), la carrera de potencia (Después la activación de una chispa o la inyección de combustible en el aire comprimido, la mezcla se quema y empuja el pistón hacia abajo) y la carrera de escape (el pistón se mueve hacia arriba mientras se abre la válvula de escape para expulsar los gases residuales), cíclicamente.

- o Según el número de tiempos: Dos tiempos.

Se basa en el ciclo de cuatro tiempos, pero las acciones se producen en dos eventos: Carrera descendente (Carreras de potencia, admisión y escape) y carrera ascendente (Carrera de compresión).

- Por el método de encendido: Encendido por compresión.

Es el ciclo típico de un motor diésel, en el cual el fluido que entra y se comprime en la cámara de combustión es solo aire y luego se inyecta el combustible. El ciclo se basa en una compresión isentrópica, una expansión isobárica, una expansión isentrópica y una descompresión isocórica. [NUCL_DC]

- Por el método de encendido: Encendido por chispa

Es el ciclo común utilizado en un motor de gasolina, que necesita una chispa para iniciar el proceso de combustión. Su ciclo está formado por una compresión isentrópica, una compresión isocórica, una expansión isentrópica y una descompresión isocórica. [NUCL_OC]

- Rotatorio
 - Wankel

Es un motor que, en lugar de utilizar fuerzas recíprocas, un rotor dentro de una carcasa produce las cuatro carreras de admisión, compresión, combustión y escape.

- Combustión continua.
 - Turbina de gas

Consiste en un compresor, una cámara de combustión y una turbina que siguen el ciclo Brayton (Proceso adiabático - compresión, proceso isobárico - combustión, proceso adiabático - expansión y proceso isobárico - escape). [CAST18]

- Motor de cohete

Es un motor basado en la Tercera Ley de Newton ("Para cada acción hay una reacción igual y opuesta") y la fuerza es el empuje producido por la combustión de un combustible y un oxidante. [HALL15]

Como los motores recíprocos son los más utilizados, serán los analizados.

EMISIONES

El principio de funcionamiento de los automóviles es el uso de una reacción química para producir movimiento con un motor recíproco IC. El oxidante es el oxígeno del aire y el combustible, la gasolina o el diésel. Idealmente, la oxidación de los hidrocarburos contenidos en el combustible con el aire da como resultado dióxido de carbono (CO_2), agua (H_2O) y calor. Pero el aire está compuesto principalmente de nitrógeno (80%) y oxígeno (20%), los combustibles no son hidrocarburos puros y su mezcla no está completa, por lo tanto, los residuos resultantes son [JANI11]:

- Hidrocarburo (C_nH_m): Es un contaminante producido cuando no todo el combustible ha reaccionado con el oxígeno debido al efecto conocido como 'wall-quenching', depósitos de carbón o algún malfuncionamiento de los sistemas del motor. Además, hay un aumento en su formación cuando la relación aire/combustible es rica o demasiado pobre. Existe una inmensa variedad de hidrocarburos, pero los dos más tóxicos son los compuestos orgánicos volátiles

- (los COV, siendo el benceno el más peligroso) y los hidrocarburos aromáticos policíclicos (los HAP, siendo el benzo[a]pireno el contaminante más importante).
- Monóxido de carbono (CO): es el resultado del combustible parcialmente quemado de una combustión rica causada por la inyección de combustible a alta presión, aire frío, inyectores defectuosos o mientras se calienta el motor.
 - Óxidos de nitrógeno (NOx): se crean especialmente en condiciones de carga pesada con altas temperaturas y presiones, y el más común es el óxido nítrico. Es más común entre una combustión estequiométrica y una magra.
 - Óxidos de azufre (SOx): su causa de formación es la presencia de azufre en los combustibles, pero esto es necesario para la lubricación adecuada del motor.
 - Material particulado (PM): es una asociación de elementos minúsculos de materia sólida suspendidos en gas o líquido. Su composición difiere entre los tipos de motores y se clasifican según su tamaño PM10, PM2.5, PM1 y ultrafino.
 - Dióxido de carbono (CO₂): es el gas de efecto invernadero más importante y su formación solo puede reducirse disminuyendo el combustible o con una combustión rica o pobre. [SCHAF95]

EFEECTO INVERNADERO

Es el proceso natural utilizado para calentar la Tierra. Parte de la radiación del Sol que llega a la Tierra es absorbida por ella y el resto es emitida de nuevo, pero los gases de efecto invernadero en la atmósfera la absorben, lo que resulta en un calentamiento de la Tierra. Los gases de efecto invernadero más comunes son [SOLO17]:

- Vapor de agua (H₂O): Es el gas con mayor influencia en el efecto (80%), pero es un gas producido de forma natural y tiene una vida útil corta. A medida que aumenta la temperatura, más agua se evapora de los océanos y esto produce más efecto invernadero, lo que resulta en temperaturas más altas y, por lo tanto, una mayor evaporación del agua, que constituye un circuito de retroalimentación.
- Dióxido de carbono (CO₂): Es el gas de efecto invernadero más importante emitido por las actividades humanas y los procesos naturales. Forma parte del ciclo del carbono y, aunque no es el gas más potente, aumenta rápidamente su concentración con el tiempo.
- Metano (CH₄): Se produce en océanos, volcanes, desechos animales y, especialmente, en humedales. La contribución humana a este gas se debe al aumento del ganado.
- Óxido nitroso (N₂O): Se origina principalmente en fuentes naturales como seres vivos, pero también existen mecanismos de reducción naturales como bacterias y la radiación ultravioleta.
- Ozono troposférico (O₃): El ozono puede ser beneficioso (capa de ozono), dañino (superficial) o tratado como un gas de efecto invernadero (troposfera) en función de su altitud.
- Gases fluorados: son los gases de efecto invernadero más potentes, ya que su vida útil puede ser de hasta 50.000 años, pero sus concentraciones son bajas.

Las causas del efecto invernadero se pueden dividir en [EUCC14] [BODE09] [HEC_]:

- Causas antropogénicas: su origen se encuentra en actividades humanas como la quema de combustibles fósiles, la deforestación, el aumento de ganado, los fertilizantes que contienen nitrógeno, los gases fluorados y los residuos industriales y vertederos.

- Causas no antropogénicas: existen causas naturales como la radiación solar, los volcanes, la órbita terrestre y los océanos.

DOWNSIZING

El ‘downsizing’ es una tendencia en la industria automotriz basada en la reducción del desplazamiento del motor para reducir el consumo de combustible y las emisiones de los motores. En combinación con esta reducción, se aplican algunas tecnologías para aumentar la eficiencia, manteniendo las características de rendimiento. Esto se ha establecido en base a los estándares Euro.

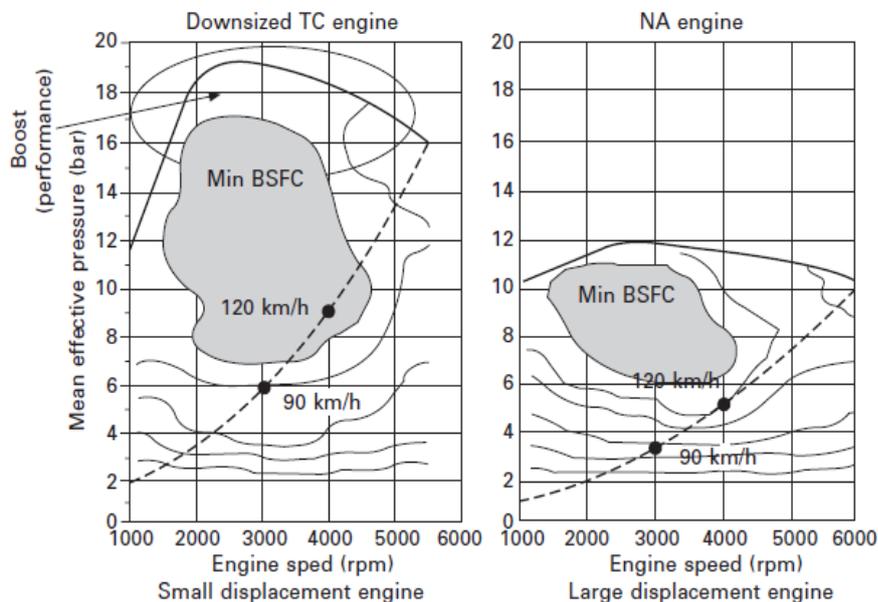


Figure 1: Comparación entre un motor ‘downsized’ TC y un motor NA en aspecto de presión efectiva media a diferentes velocidades de motor [ZHAO10]

Para mejorar las características de rendimiento de los motores downsized, se han adoptado las siguientes tecnologías basadas en el aumento de la presión efectiva media:

- Inducción forzada (FI): Además de la inducción del aire producido por la succión del pistón, se utilizan algunos mecanismos que incrementan la relación de compresión efectiva:
 - o Sobrealimentación: Un compresor está conectado al cigüeñal y comprime el aire antes de que este ingrese en el cilindro. Puede ser un compresor rotativo (tipo Roots, solo crea desplazamiento, no compresión en sí o tipo paleta) o un compresor centrífugo, que se basa en el uso de la fuerza centrífuga para aumentar la presión del fluido y se usa comúnmente en la turbo alimentación. La principal desventaja es la sustracción de potencia del motor. [ARIA08] [JAIN12]

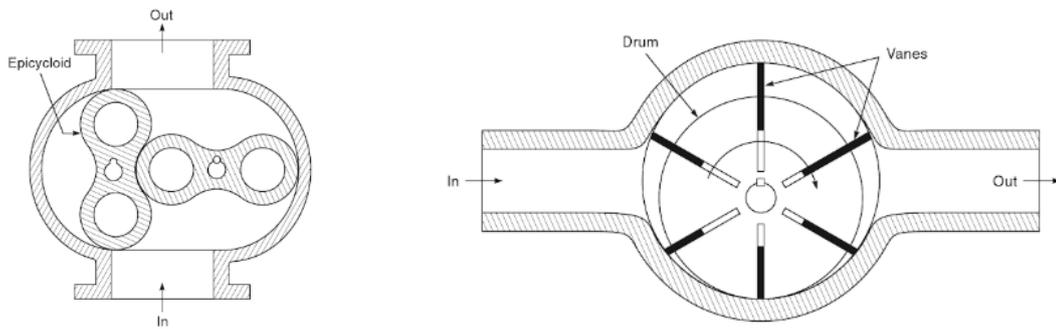


Figure 2: Roots type (Left) and vanes type (Right) compressor [JAIN12]

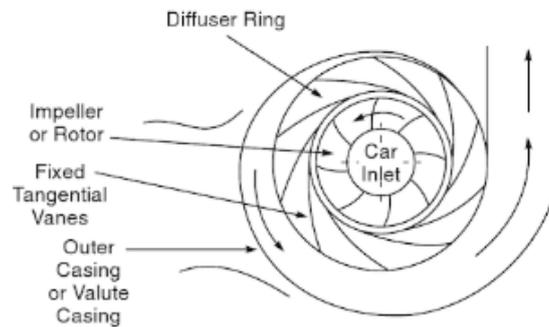


Figure 3: Centrifugal compressor [JAIN12]

- Turbocompresor: Se basa en el sistema de sobrealimentación, pero en lugar de estar acoplado al motor, el compresor es impulsado por una turbina que se mueve por los gases de escape de alta velocidad. La desventaja de esta tecnología es el ‘lag’ producido por los gases de baja velocidad a bajas revoluciones. [ALON09]
- Dispositivo de compresión de onda: Es un sistema basado en la teoría de si dos fluidos están en contacto en un espacio largo y estrecho con presiones diferentes igualan sus presiones antes de empezar a mezclarse entre sí. El aire fresco está en contacto con los gases de escape antes de alcanzar el cilindro. Tiene ‘lag’ como el turbocompresor y un aumento de la temperatura del aire fresco como desventajas. [COST17] [HEYW88]
- Inyección directa (DI): La inyección de gasolina se realiza en la cámara de combustión en lugar del colector de admisión. La ventaja más importante es la posibilidad de combinar carga estratificada y carga homogénea inyectando el combustible varias veces durante el mismo ciclo. El resultado es una optimización del rendimiento del motor o bajo consumo y emisiones cuando sea necesario. [ALON09]
- Sincronización de válvula variable (VVT), elevación de válvula variable (VVL) y sincronización y elevación de válvula variable (VVTL): Resuelve el problema de tener un evento de válvula único para todas las velocidades del motor, en cambio, cambia según la necesidad de rendimiento o de reducción de emisiones en condiciones de carga ligera. Básicamente mejora el llenado del cilindro.

Otra tendencia, que es una variación del ‘downsizing’, es la de ‘rightsizing’. Su objetivo no es encontrar el desplazamiento mínimo, sino el óptimo. También combina

todas las tecnologías del ‘downsizing’ como inducción forzada, inyección directa y sincronización variable de válvulas. Algunos autores definen un índice de dimensionamiento basado en la relación entre la carrera del pistón y el diámetro del cilindro y la conclusión fue que esta relación tiene un impacto mínimo en la eficiencia teórica. [SROK19]

MOTORES DOWNSIZED Y EFECTO INVERNADERO

Las emisiones de gases de efecto invernadero han disminuido en las últimas tres décadas aprox. un 20% y la principal fuente ha sido el sector energético (Alrededor del 80%).

Las emisiones de dióxido de carbono han disminuido un 17%, pero el sector del transporte por carretera es el único que ha aumentado y es el segundo contribuyente.

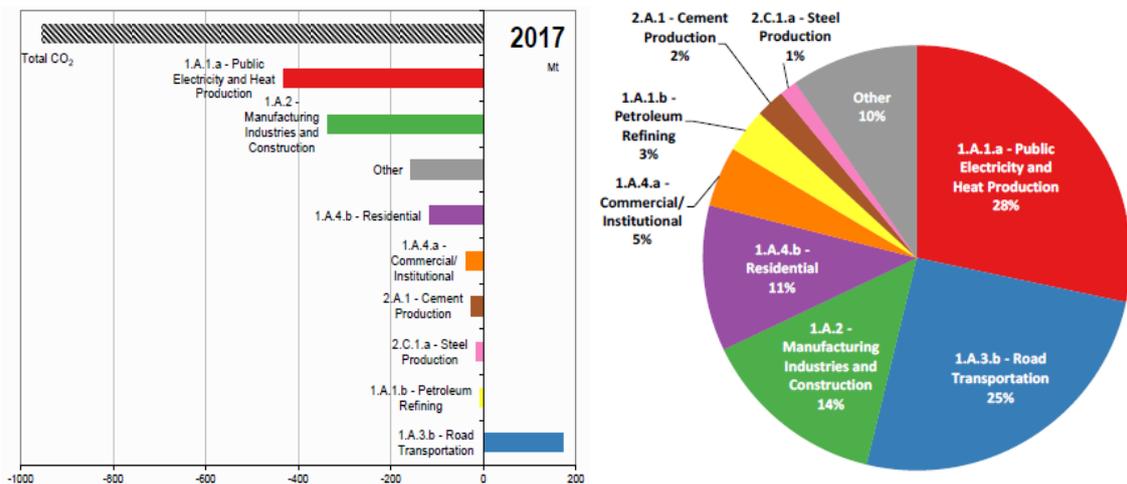


Figure 4: Change of carbon dioxide emissions from 1990 to 2017 (Left) and main sources in 2017 (Right) [EEA_19AEUGHG119]

El metano contribuye con el 11% de la masa total de los gases de efecto invernadero y ha disminuido un 35%, siendo el principal contribuyente a sus emisiones los desechos animales, incrementado por el ganado. El óxido nitroso es responsable del 6% de todas las emisiones de gases de efecto invernadero y ha disminuido en más del 40% entre 1990 y 2010 y se mantiene casi constante hasta 2017. Los gases fluorados tienen un 3% de la proporción de emisiones de gases de efecto invernadero y son los únicos gases que han aumentado en las últimas tres décadas alcanzando un 40% más en 2014 en comparación con 1990.

La tendencia de reducción de tamaño se ha aplicado reduciendo progresivamente el desplazamiento del motor en torno al 10%, el consumo de combustible aprox. 27% y las emisiones de dióxido de carbono hasta un 30%, pero ha habido un aumento del 25% en la potencia del motor. La compañía de automóviles más vendida es Volkswagen y ha disminuido el desplazamiento de sus motores e implementado tecnologías de turbo alimentación e inyección directa en el 83% y 99% de su producción, respectivamente. Además, hay un análisis de las mejoras causadas por la sincronización variable de la

válvula y la inyección directa, que resultan en una mayor potencia específica y un menor consumo específico en ambos sistemas en comparación con su antecesor, el carburador y la tecnología de válvula fija y única.

CONCLUSIONES

Las conclusiones más importantes para este proyecto son:

- Las emisiones de gases de efecto invernadero han disminuido en las últimas tres décadas, pero esta disminución no ha sido suficiente para prevenir el aumento de las temperaturas.
- El sector de actividad humana con mayor influencia en este efecto es el energético con aprox. 80% del efecto global.
- El principal responsable de este efecto es el dióxido de carbono y su principal contribuyente es la producción de electricidad que junto con el transporte por carretera suman el 50% del total.
- El transporte por carretera es el único sector que no ha disminuido sus emisiones de dióxido de carbono en las últimas tres décadas.
- La reducción de la capacidad del motor significó una reducción del 27% en el consumo de combustible mixto, una disminución del 30% de las emisiones de dióxido de carbono y un 24% de las emisiones de contaminantes en 2016.
- Si los nuevos motores de los automóviles han estado reduciendo sus emisiones, pero el transporte por carretera los ha incrementado, la razón es que la cantidad de automóviles ha aumentado y la edad promedio de ellos.
- La solución para la situación actual del incrementado efecto invernadero, causado en parte por el sector del transporte por carretera, radica en la expansión de la tendencia del ‘downsizing’ y la limitación progresiva de la circulación de automóviles viejos con altos índices de emisiones.

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SUMMARY OF THE PROJECT

INTRODUCTION

Internal combustion (IC) engines have enabled an incredible development of the human activities, including automobiles which are part of the everyday life of humans. Part of these activities responsible for this development have resulted in the upgrowing emission of greenhouse gases that produce the so-called greenhouse effect.

As it is one of the main concerns for nowadays society and one of the possible solutions for reducing the contribution of automobiles is the trend known as downsizing, both will be described separately, analyzed and compared in this project.

IC ENGINES

IC engines are based on the oxidation of a fuel in a combustion chamber using this mixture as the working fluid for the engine. They can be classified as:

- Reciprocating
 - According to the number of strokes: Four stroke

It consists in a process divided in four events: Intake stroke (The inlet valves are opened and the piston moving downwards to absorb the fluid), compression stroke (The piston moving upwards compress the fluid to lower the ignition temperature), power stroke (After the activation of a spark or the injection of fuel in the compressed air, the mixture combusts and push the piston downwards) and exhaust stroke (The piston moves upwards while the exhaust valve is opened to expel the residual gases), repeatedly.

- According to the number of strokes: Two stroke

It is based on the four stroke cycle, but the actions occur in two events: Down stroke (Power, intake and exhaust strokes) and up stroke (Compression stroke).

- By the ignition method: Compression-ignition

It is the typical cycle of a diesel engine, in which the fluid entering and being compressed in the combustion chamber is only air and afterward the diesel fuel is injected.

The cycle is based on an isentropic compression, an isobaric expansion, an isentropic expansion and an isochoric decompression. [NUCL_DC]

- By the ignition method: Spark-ignition

It is the common cycle used in a gasoline engine, which needs a spark to initiate the combustion process. Its cycle is formed by an isentropic compression, an isochoric compression, an isentropic expansion and an isochoric decompression. [NUCL_OC]

- Rotary
 - Wankel

It is an engine that instead of using reciprocating forces a rotor inside a housing creates the four strokes of intake, compression, combustion and exhaust.

- Continuous combustion
 - Gas turbine

It consists in a compressor, a combustor and a turbine following the Brayton cycle (Adiabatic process – compression, isobaric process – combustion, adiabatic process – expansion and isobaric process – exhaust). [CAST18]

- Rocket engine

It is an engine based on the Newton's Third Law of Motion ('For every action there is an equal and opposite reaction') and the force is the thrust produced by the combustion of a fuel and oxidizer. [HALL15]

As reciprocating engines are the most used, they will be the ones analyzed.

EMISSIONS

Automobiles working principle is the use of a chemical reaction to produce movement with an IC reciprocating engine. The oxidizer is the oxygen of the air and, the fuel, gasoline or diesel. Ideally, the oxidation of the hydrocarbons contained in the fuel with air results in carbon dioxide (CO₂), water (H₂O) and heat. But the air is composed mainly of nitrogen (80%) and oxygen (20%), fuels are not pure hydrocarbons and their mixture is not complete, thus, the resultant residues are [JANI11]:

- Hydrocarbon (C_nH_m): It is a pollutant produced when not all the fuel has reacted with the oxygen because of the effect known as wall quenching, carbon deposits or some malfunction of the engine's systems. Furthermore, there is an increase in its formation when the air/fuel ratio is rich or too lean. There is an immense variety of hydrocarbons, but the two more toxic ones are volatile organic compounds (VOCs, benzene being the most hazardous) and polycyclic aromatic hydrocarbons (PAHs, being benzo[a]pyrene the most important pollutant).
- Carbon monoxide (CO): It is partially burned fuel result of a rich combustion caused by high pressure fuel injection, cold air, defective injectors or while warming the engine.

- Nitrogen oxides (NO_x): They are created especially in heavy load conditions with high temperatures and pressures and the most common is the nitric oxide. It is more common between a stoichiometric and a lean combustion.
- Sulfur oxides (SO_x): Their cause of formation is the presence of sulfur in fuels, but this is needed for the proper lubrication of the engine.
- Particulate matter (PM): It is an association of minuscule elements of solid matter suspended in gas or liquid. Their composition differs between the types of engines and they are classified based on their size PM₁₀, PM_{2,5}, PM₁ and ultrafine.
- Carbon dioxide (CO₂): It is the most important greenhouse gas and its formation can only be reduced by decreasing the fuel consumption or with a rich or lean combustion. [SCHAF95]

GREENHOUSE EFFECT

It is the natural process used to warm the Earth. Part of the Sun's radiation which reaches the Earth is absorbed by it and the rest is emitted back but the greenhouse gases in the atmosphere absorb it, resulting in a heating of the Earth. The most common greenhouse gases are [SOLO17]:

- Water vapor (H₂O): It is the gas with more influence in the effect (80%), but it is a natural produced gas and it has a short lifetime. As the temperature rises more water is evaporated from oceans and this produces more greenhouse effect, which results in higher temperatures and, thus higher water evaporation, constituting a feedback loop.
- Carbon dioxide (CO₂): It is the most important greenhouse gas emitted from human activities and natural processes. It forms part of the carbon cycle and even it is not the most powerful gas, it is rapid increasing its concentration over time.
- Methane (CH₄): It is produced in oceans, volcanoes, animal waste and, especially, in wetlands. The human contribution to this gas is the increasing livestock.
- Nitrous oxide (N₂O): It is mainly originated in natural sources as living beings, but there are also natural reduction mechanisms as bacteria and ultraviolet radiation.
- Tropospheric ozone (O₃): Ozone can be beneficial (Ozone layer), harmful (Surface) or treated as a greenhouse gas (Troposphere) depending on its altitude.
- Fluorinated gases: They are the most powerful greenhouse gas as its lifetime can be up to 50.000 years, but their concentrations are low.

Causes for the greenhouse effect can be divided in [EUCC14] [BODE09] [HEC_]:

- Anthropogenic causes: Its origin is in human activities as burning fossil fuels, deforestation, increasing livestock, fertilizers containing nitrogen, fluorinated gases and industrial waste and landfills.

- Non-anthropogenic causes: There are natural causes as solar radiation, volcanoes, Earth's orbit and oceans.

DOWNSIZING

Downsizing is a trend in the automotive industry based in the reduction of the engine displacement to reduce the fuel consumption and emissions from engines. In combination with this reduction some technologies are applied to increase the efficiency, maintaining the performance characteristics. This has been established based on the Euro standards.

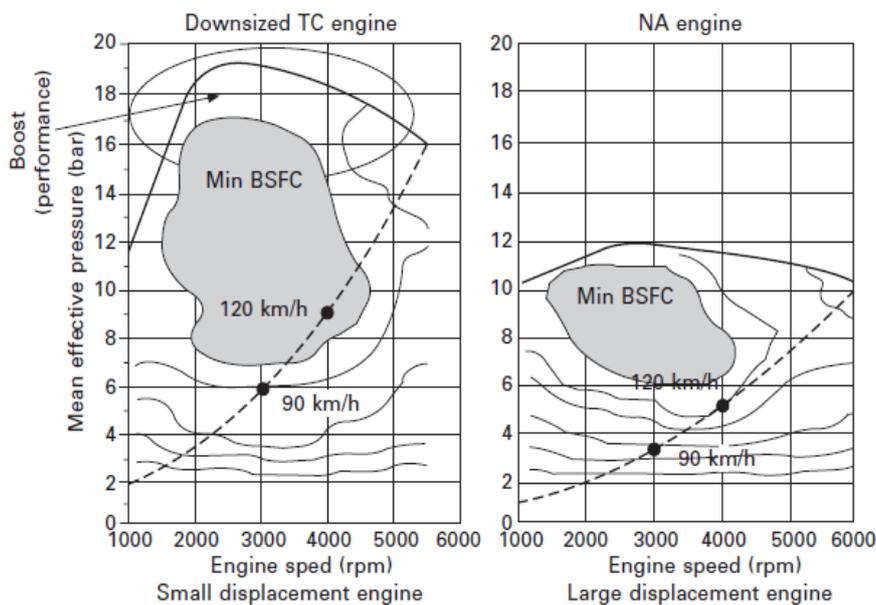


Figure 1: Comparison between a downsized TC engine and NA engine in aspect of mean effective pressure over different engine speed [ZHAO10]

In order to improve the performance characteristics of the reduced engines, the following technologies have been adopted based on increasing the mean effective pressure:

- Forced induction (FI): In addition to the induction of air produced by the piston suction, some mechanisms that increment the effective compression ratio are used:
 - o Supercharging: A compressor is engaged to the crankshaft and it compresses the air before entering the cylinder. It can be a rotary compressor (Roots type, it only creates displacement not compression itself, or vane type) or centrifugal compressor, which is based in the use of centrifugal force to increase the fluid's pressure and it is commonly used in turbocharging. The main disadvantage is the power subtraction of the engine. [ARIA08] [JAIN12]

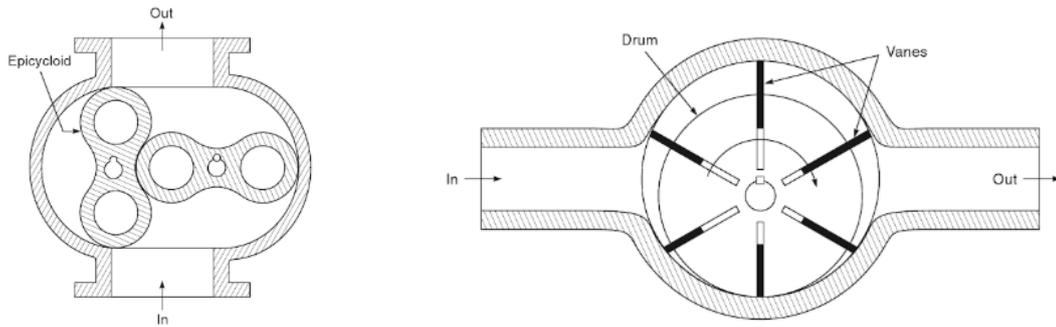


Figure 2: Roots type (Left) and vanes type (Right) compressor [JAIN12]

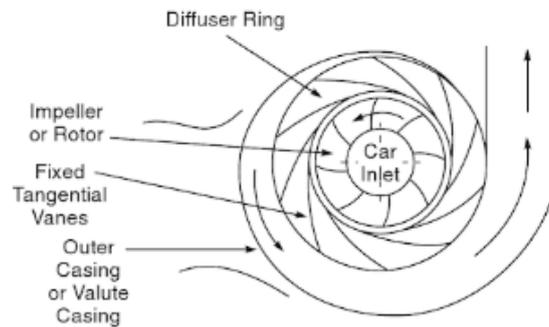


Figure 3: Centrifugal compressor [JAIN12]

- Turbocharging: It is based on the supercharging system but instead of being coupled to the engine, the compressor is driven by a turbine which is moved by the high speed exhaust gases. The disadvantage of this technology is the initial lag produced by the low speed gases at low rpm. [ALON09]
- Wave-compression device: It is a system based on the theory of if two fluids are in contact in a long and narrow space having different pressures both equalize their pressures more rapidly than they mix with each other. The fresh air is in contact with the exhaust gases before reaching the cylinder. It has lag as the turbocharging and rising fresh air temperatures as disadvantages. [COST17] [HEYW88]
- Direct injection (DI): The injection of gasoline is made in the combustion chamber instead of the intake manifold. The most important advantage is the possibility to combine stratified-charge and homogeneous-charge by injecting the fuel multiple times during the same cycle. The result is an optimization of the engine performance or low consumption and emissions when needed. [ALON09]
- Variable valve timing (VVT), variable valve lifting (VVL) and variable valve timing and lifting (VVTL): It solves the problem of having a unique valve process for all the engine speeds, instead it changes depending on the need of performance or reduced emissions in light-load conditions. It basically improves the filling of the cylinder.

Another trend, that is a variation of the downsizing, is the rightsizing. Its objective is no longer finding the minimum displacement, but the optimal one. It also combines all the technologies of downsizing for forced induction, direct injection and variable valve timing. Some authors define a rightsizing index based on the relation between the piston

stroke and cylinder bore and the conclusion was that its relation has a minimal impact in the theoretical efficiency. [SROK19]

DOWNSIDED ENGINES AND GREENHOUSE EFFECT

The greenhouse gases emissions have been decreasing in the last three decades approx. 20% and the main source has been the energy sector (Around 80%).

The carbon dioxide emissions have decreased 17%, but the road transportation sector is the only one that has increased, and it is the second contributor.

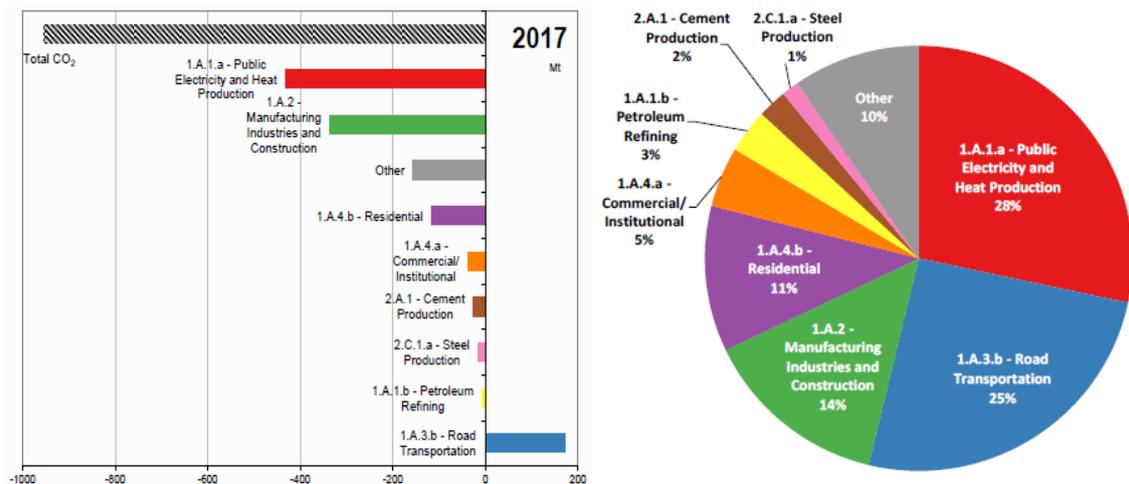


Figure 4: Change of carbon dioxide emissions from 1990 to 2017 (Left) and main sources in 2017 (Right) [EEA_19AEUGHG119]

Methane contributes with 11% of the total mass of the greenhouse gases and they have decreased 35%, being the major contributor to its emissions the animal waste, increased by the livestock. Nitrous oxide is responsible for 6% of all the greenhouse gases emissions and it has decreased over 40% from 1990 to 2010 and maintain almost constant till 2017. Fluorinated gases have a 3% of the share of greenhouse gases emissions and they are the unique gases that have increased over the last three decades reaching up 40% more in 2014 compared to 1990.

The downsizing trend has been applied progressively reducing the engine displacement around 10%, the fuel consumption approx. 27% and the carbon dioxide emissions up to 30%, but there has been an increase of 25% in the engine power. The best selling automobile company is Volkswagen and it has decrease their engines displacement and implement turbocharging and direct injection technologies in 83% and 99% of their production, respectively. Also, there is an analysis of the improvements caused by variable valve timing and direct injection resulting in a higher specific power and lower brake specific fuel consumption in both systems compared to their predecessor the carburetor and the fixed and single valve technology.

CONCLUSIONS

The most important conclusions for this project are:

- Greenhouse gases emissions have been decreasing over the last three decades but this decrease has not been enough for preventing the increase of temperatures.
- The human activity sector with higher influence in this effect is the energy one with an approx. 80% of the overall effect.
- The main responsible for this effect is the carbon dioxide and its major contributor is the production of electricity together with the road transportation accounting 50%.
- Road transportation is the only sector which have not decreased its emissions of carbon dioxide the last three decades.
- The reduction of the engine capacity meant a reduction of 27% in the mixed fuel consumption, a decrease of 30% of the carbon dioxide emissions and a 24% of pollutants emissions in 2016.
- If the new car engines have been decreasing their emissions, but the road transportation have been increasing them, the reason is that the number of cars has been increasing and their average age with them.
- The solution for the actual situation of enhanced greenhouse effect, partially caused by the road transportation sector, lies in the expansion of the downsizing trend and the progressive limitation of circulation of old cars with high emission indexes.

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*A mi familia y, en especial,
a mis padres y mi hermana
por habérmelo dado todo*

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1. INTRODUCTION

1.1. Proposal of the problem

Internal combustion (IC) engines have induced an enormous impact in the development of human being, from the IC engine of an everyday automobile, to the IC engine that produces energy for a generator used in case of an emergency as backup power. Therefore, it has been developed during years since the first modern IC engine created by Nikolaus Otto in 1876, with the collaboration of Gottlieb Daimler and Wilhelm Maybach [NEW_18]. Even so, there have been many problems related to this such as highly fuel expense with poor efficiency (About 20% of mechanical efficiency [NEW_18]) and the creation of contaminants (Sulfur oxides SO_x , nitrogen oxides NO_x , carbon dioxide CO_2 , soot... [NEW_18]). The carbon dioxide is one of the greatest responsible for the so-called greenhouse effect.

The immense increase of greenhouse gases in the last years has been an important issue, due to its effect in the global warming. Since its origin, which is considered to be at the end of the 18th century with the Industrial Revolution [RUTL11], it is observable the enormous increment of greenhouse gases concentrations (See *Figure 1*).

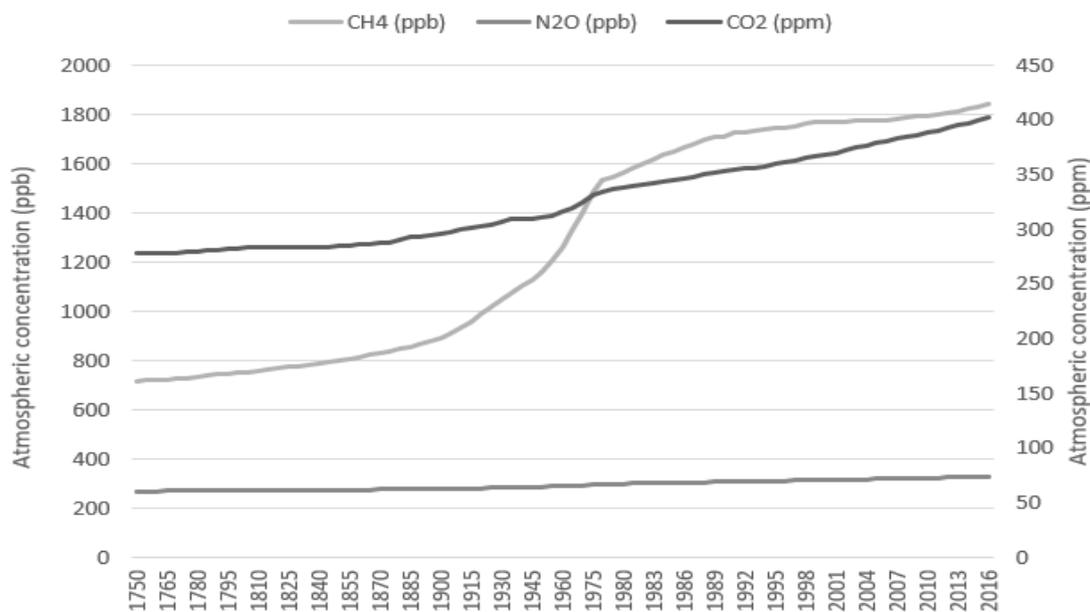


Figure 1: Trends in atmospheric concentration of CO_2 , CH_4 and N_2O [EEA_19]

From *Figure 1*, it is observable an increase of all the three chemical compounds, that are greenhouse gases, but especially from the CH_4 which since 1750 has gained 157% (approx.) till 2016. Also, the N_2O has increased around 50% and the CO_2 has grown 45% in its concentration. It must be considered that the CO_2 is measured in ppm instead of ppb as the other two compounds.

Introduction

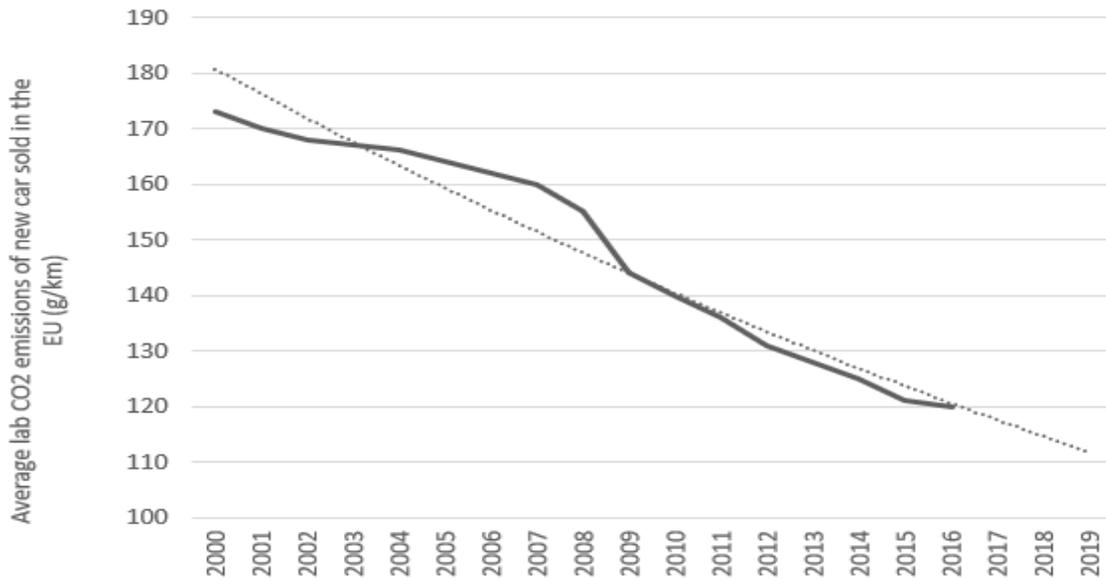


Figure 2: Evolution of CO₂ emissions from new automobiles from 2000 to 2016 [TODT18]

Recently, new studies have appeared analyzing the evolution of CO₂ emissions from automobiles and they have been decreasing over the years since 2000 (See *Figure 2*). We can extrapolate from the data until 2016, that in 2019 the emissions should be below 120 g/km, which leads to a decrease from the year 2000 till now of 35% (approx.).

The downsizing technology is a trend for IC engines that started in the 90s, basically consisting in the decreased size of the engine displacement in order to reduce the fuel consumption and, thus, emissions, gaining the power loss from technologies like turbocharging, supercharging, direct injection and variable valve timing and lifting. Although, it has been one of the main trends in the development of IC engines some experts declare that it is no longer the optimum solution replacing it by the so-called rightsizing, a technic that consists not only in finding the minimum engine displacement, but the optimum one.

1.2. Motivation

The main purpose of this project is to evaluate if the downsizing (or rightsizing) technic is a viable solution to the current problem of the emission of greenhouse gases emission, by analyzing its progress of technology and emissions. In recent years, the global warming, which is believed to be consequence of the enhanced greenhouse effect, has been one of the main concerns of the world population (*Figure 3*).

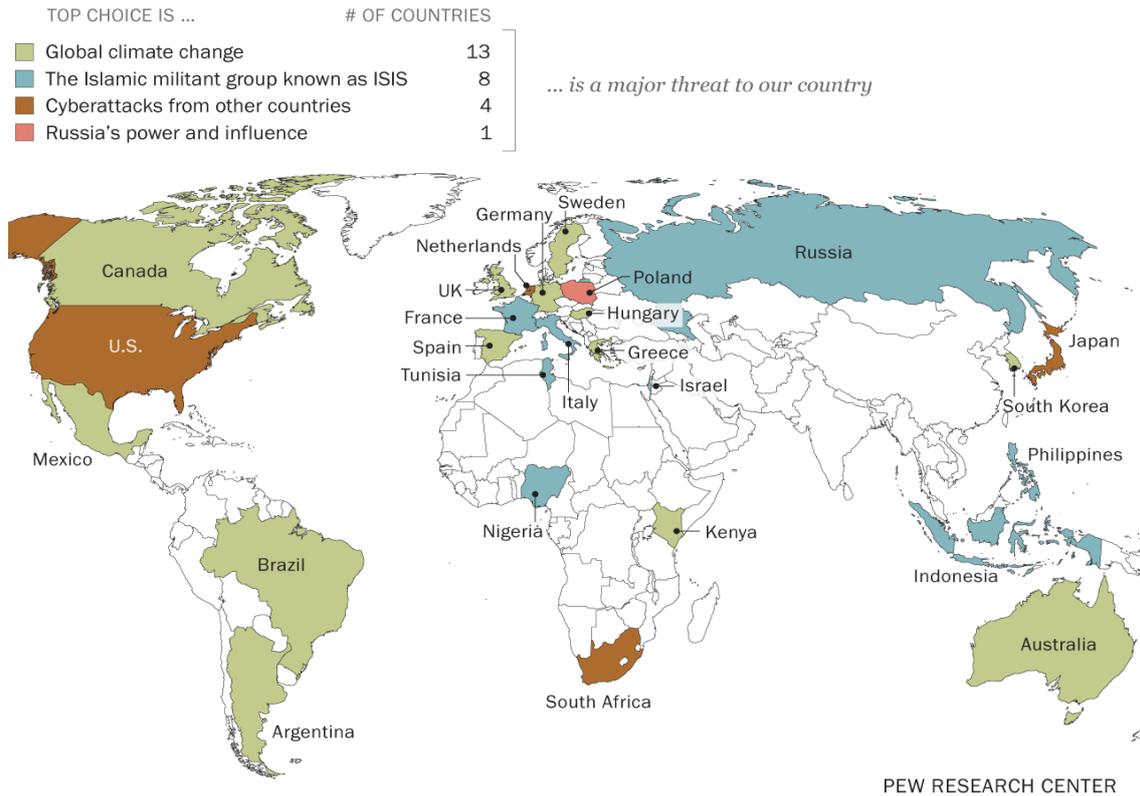


Figure 3: Top threats according to different countries of the world [POUS19]

Therefore, many other alternatives have appeared such as electrical, hydrogen and alternative fuel cars. While a large and growing part of the population considers the electric cars the ultimate solution to the problem, the reality is that they are far from being a viable solution today. To complete this evolution, the generation of electricity should be as clean as possible (Europe-28, 2017: Conventional thermal 48.3%, nuclear 25.6%, hydro 10.3%, wind 11.7%, solar 4%, geothermal and others 0.2% [EURO18EG]) and during this transformation an alternative is needed.

In this project the causes to produce greenhouse gases will also be analyzed and in Figure 4 it is observable that one of the greatest causes of the greenhouse effect and in continuous growth is the transport.

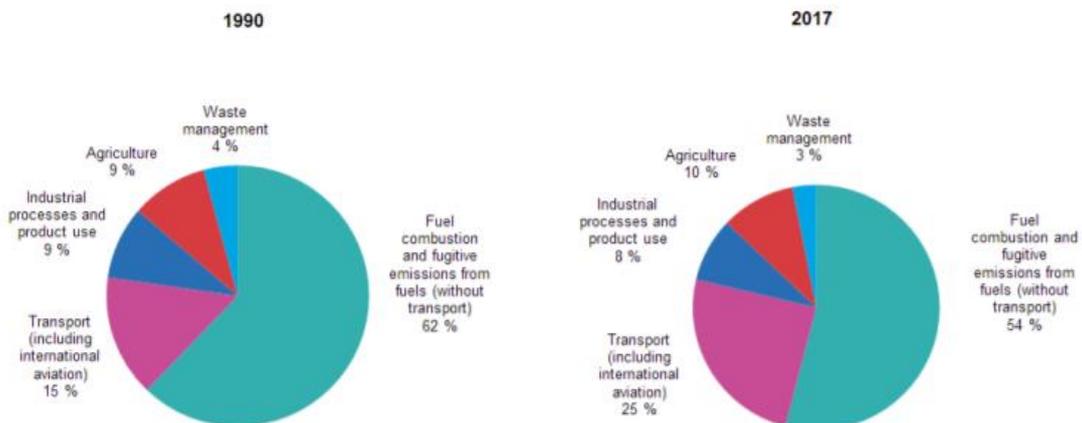


Figure 4: Sources of greenhouse gases in 1990 and 2017 in Europe [EURO19GHGE]

1.3. Objectives of the project

The main aim of this project is the analysis of European greenhouse gases emission from mobile sources in terms of downsizing and rightsizing trends in automotive industry. More precisely, there are the following objectives:

- Evaluate the exhaust emission composition of IC engines
- Analyze the working principle of the downsizing engines
- Verify how has been the implementation of downsizing engines in Europe in the recent years
- Evaluate the improvement of downsizing engines compared with the previous engines in terms of greenhouse gases emission
- Comparison between anthropogenic and non-anthropogenic theories in the greenhouse effect evolution
- Verify if the downsizing engines are the best solution for the greenhouse effect in the present.

2. IC ENGINES

2.1. Work characteristics

An IC engine is any device where the fuel and oxidizer are part of the working fluid and the mix combustion occurs inside of a combustion chamber. This produces an exothermic reaction and the resulting gases of high temperature and pressure expand causing movement to the pistons, turbine blades or nozzle that are in contact with. Mainly, the combustion is produced periodically.

They are classified based on their working design:

- Reciprocating
 - o According to the number of strokes: Two strokes or four strokes
 - o By the ignition method: Compression-ignition or spark-ignition. Sabathe cycle
- Rotary
 - o Wankel
- Continuous combustion
 - o Gas turbine
 - o Rocket engine

2.2. Reciprocating

2.2.1. According to the number of strokes: Four-stroke

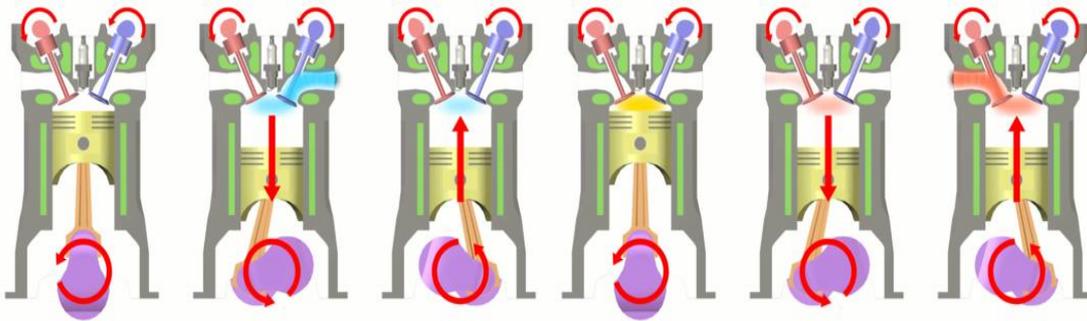


Figure 5: Initial position, intake stroke, compression stroke, activation of the spark plug, power stroke and exhaust stroke of a four-stroke gasoline engine [WIKI19FSE]

Four events occur in this process:

- 1) **Intake stroke:** The piston moves from the top dead center (TDC) to the bottom dead center (BDC), at the same time the inlet valves are opened, creating vacuum, so the air and fuel enter the combustion chamber.
- 2) **Compression stroke:** The piston moves from the BDC to the TDC, while all the valves are closed, and the air or fuel-air mixture gets compressed. Depending on the engine, at the end of the stroke, a spark plug activates combustion.
- 3) **Power stroke:** The increased temperature and pressure of the resulting mix expands and push the piston from TDC to BDC, creating the power output.
- 4) **Exhaust stroke:** The piston moves from the BDC to the TDC, and the outlet valve is opened, so the remaining exhaust gases exit the chamber.

IC engines

2.2.2. According to the number of strokes: Two-stroke

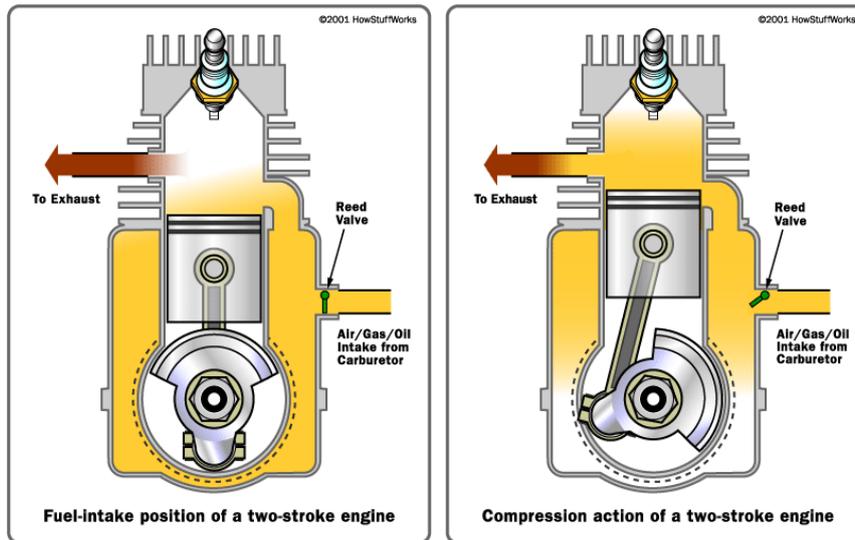


Figure 6: Down stroke and up stroke of a two-stroke gasoline engine [BRAI00]

In this operation the same actions of the four-stroke engine occur, but in two events, instead of four:

- 1) **Down stroke:** The piston advances from the TDC to the BDC, allowing flow of the fuel-air mix from the crankcase to the combustion chamber and the exhaust gases from the combustion chamber to the exhaust system.
- 2) **Up stroke:** The piston is pushed from the BDC to the TDC, compressing the air and the spark plus ignites in the mix (In gasoline engines). During this procedure the clean mix of air-fuel enters the crankcase. The expansion of the mixture makes the piston move downward.

2.2.3. By the ignition method: Compression-ignition

With this method the ignition of the fuel occurs as a result of the contact of it with the extremely hot air inside the combustion chamber. This high temperature is achieved by an intense compression of the air (Between 14:1 to 24:1, [CROL09]). It is the common method for diesel engines. It is based on the thermodynamic cycle known as Diesel cycle (See Figure 7).

Designed by Rudolf Diesel in the 1890s, it is a thermodynamic cycle based on compression-ignition. The process is divided in four stages [NUCL__DC]:

- **Isentropic compression (1-2):** This event corresponds with the compression stroke. In this stage the term compression ratio (CR) is used to describe the change of volume from the BDC to the TDC.
- **Isobaric expansion (2-3):** It is where the combustion occurs, because of the contact of the fuel with the highly compressed air.
- **Isentropic expansion (3-4):** It coincides with the power stroke, where the piston transfers the work from the gases to the crankshaft.

- **Isochoric decompression (4-1):** It is related to the exhaust stroke because at stage 4 the exhaust valves are opened and from 1 to 0 stage (BDC to TDC) the stroke occurs. The intake stroke is completed from the stages 0 to 1 (TDC to BDC), where the intake valves are closed, and the exhaust ones are closed.

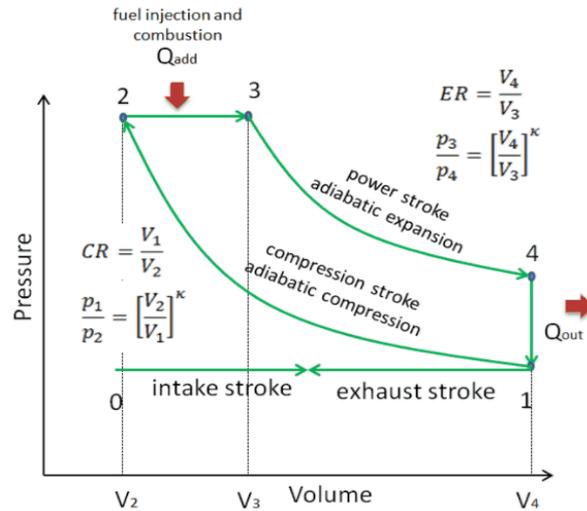


Figure 7: PV diagram of an ideal Diesel cycle [NUCL_DC]

2.2.4. By the ignition method: Spark-ignition

This technic is used in combination with the compression of the air and fuel mixture inside the cylinder, but in a lower ratio than in a compression-ignition engine (Between 7:1 and 10:1, [CROL09]). It uses the high temperature achieved in the mix of fuel and air with the compression and a spark to ignite the mix and produce the combustion. It is the typical method used in gasoline engines. This process is defined by the Otto cycle (See Figure 8).

This thermodynamic cycle was created by Nikolaus August Otto, improved by Wilhelm Maybach, in 1876. The phases of this process are the following:

- **Isentropic compression (1-2):** It coincides with the compression stroke that contains the air-fuel mixture.
- **Isochoric compression (2-3):** In this stage there is a heat applied to the mixture through the spark plug, which leads to the ignition and it is developed at constant volume.
- **Isentropic expansion (3-4):** In this phase the work is transferred from the gases to the piston which moves from the TDC to the BDC.
- **Isochoric decompression (4-1):** It is where the exhaust stroke occurs and the piston travels from the BDC to the TDC to expulse the gases from the chamber, while the exhaust valves are opened (1 to 0). After, the exhaust valves are closed, and the intake ones opened, and the intake stroke develops (0 to 1).

IC engines

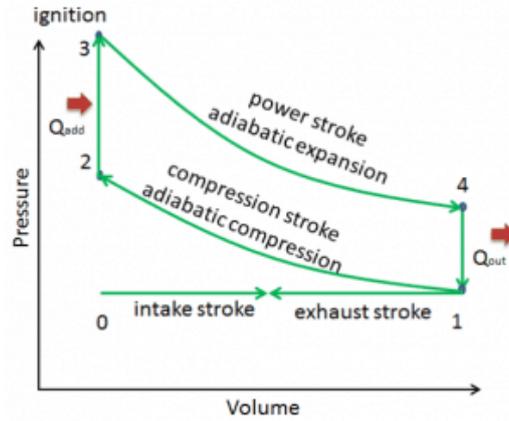


Figure 8: PV diagram of an ideal Otto cycle [NUCL_OC]

2.2.5. By the ignition method: Sabathe cycle

The Otto cycle and the Diesel cycle are ideal thermodynamic cycles that differ from reality. In the ideal Diesel cycle, the combustion is an isobaric transformation, but this is only true when applied to highly loaded and slow engines. The real cycle consists of a combustion that is close to, first, an isochoric phase and, consequent, an isobaric transformation. In non-ideal studies, it can be established that the Diesel and the Otto cycle are a particular case of a mixed cycle known as Sabathe cycle or dual cycle (See *Figure 9*) [TEXA16].

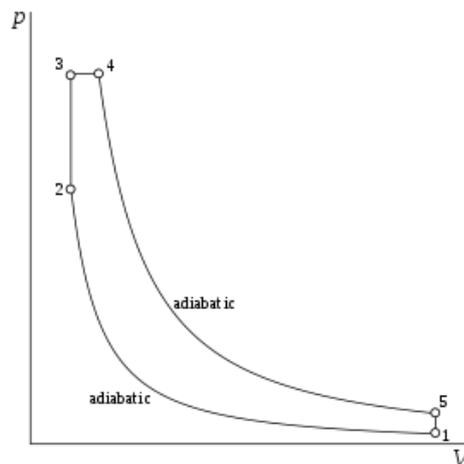


Figure 9: PV diagram of Sabathe cycle [WIKI18MDC]

- **Isentropic compression (1-2)**
- **Inserting heat at constant volume (2-3)**
- **Inserting heat at constant pressure (3-4)**
- **Isentropic expansion (4-5)**
- **Expulsion of heat at constant volume (5-1)**

2.3. Rotary

2.3.1. Wankel

Developed by Felix Wankel, in 1929, the Wankel engine converts the energy delivered by the ignition of fuel and air mixture into rotatory motion of the crankshaft.

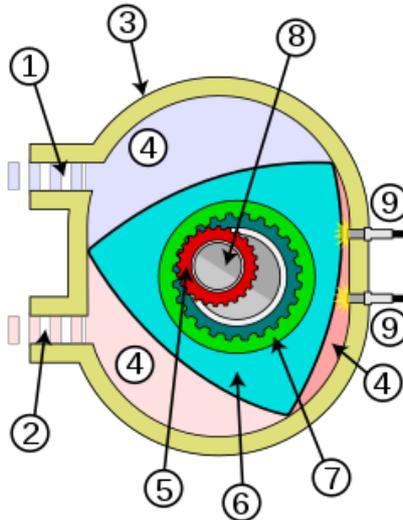


Figure 10: Wankel engine parts [WIKI19WE]

It is composed of an intake (1, Figure 10) and exhaust (2, Figure 10), a housing (3, Figure 10), chambers (4, Figure 10), a pinion (5, Figure 10), a rotor (6, Figure 10), a crown gear (7, Figure 10), an eccentric shaft (8, Figure 10) and spark plugs (9, Figure 10). It works based on a four stroke Otto cycle and, commonly, it has more than one rotor.

In this case, the four-stroke process follows the schematic represented in Figure 11.

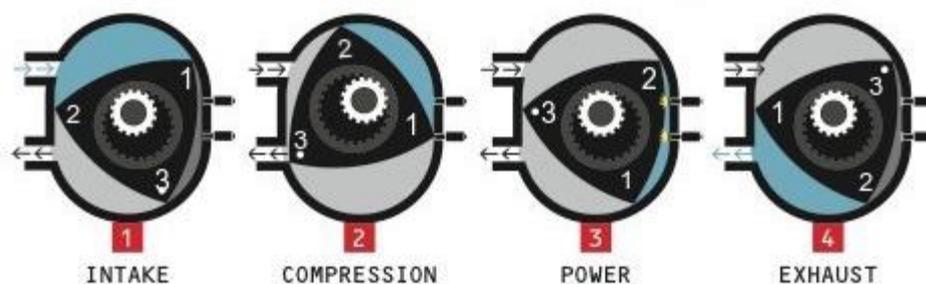


Figure 11: Work diagram of a Wankel engine [BAV116]

2.4. Continuous combustion

2.4.1. Gas turbine

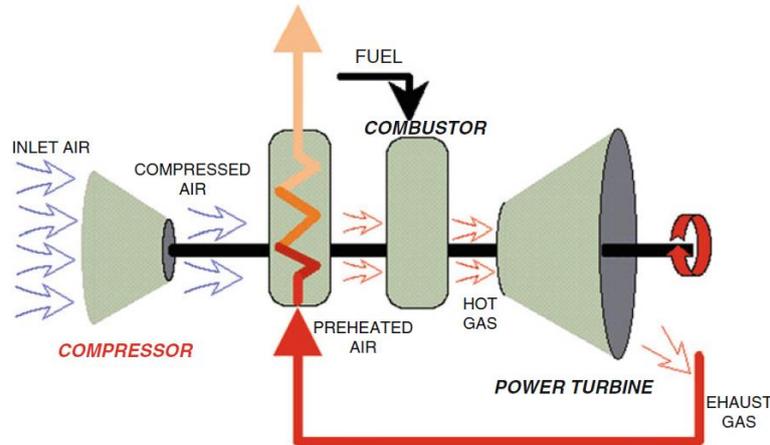


Figure 12: Schematic of gas turbine with regeneration [ZOHU15]

The working process of a turbine is based on a Brayton cycle (1 – adiabatic process, 2 – isobaric process, 3 – adiabatic process, 4 – isobaric process; Figure 13) and has 4 steps: Intake of air, compression of air, combustion of mixture, expansion and exhaust. Occasionally, the fuel is mixed with the air from the start at the intake.

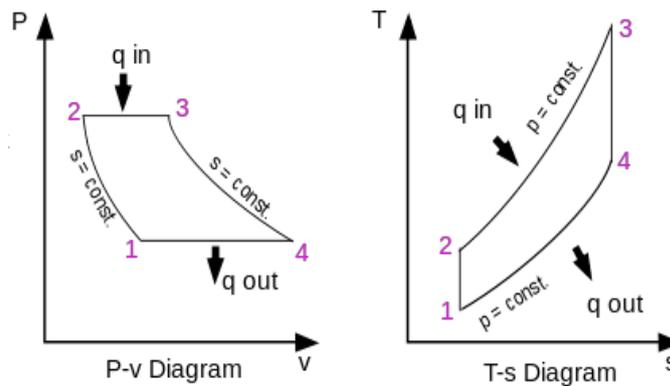


Figure 13: Idealized Brayton cycle [WIKI19BC]

It consists of a compressor, that converts the mechanical energy into gaseous energy, incrementing the total pressure of the fluid (Most of it in form of velocity) and, in combination with a diffuser, almost all pressure turns into static pressure, a combustor, where the air-fuel mix gets burnt continuously, and a turbine, where the gaseous energy of the mixture is turned into mechanical energy. [CAST18]

2.4.2. Rocket engine

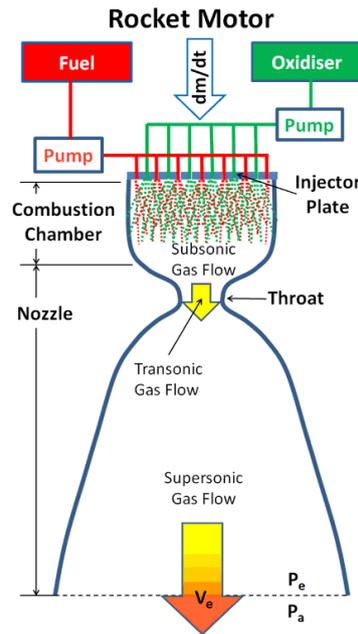


Figure 14: Scheme of a rocket engine [LAWS_]

The working principle of a rocket engine is based on ‘For every action there is an equal and opposite reaction’ (Newton’s Third Law of Motion) and based on this it produces the force that produces movement, called thrust. This thrust is produced via the combustion of a fuel and oxidizer, which results in hot exhaust that is led through a nozzle in order to accelerate it, although it produces a pressure loss. There are liquid rockets, where fuel and oxidizer are in liquid state and they are introduced into the combustion chamber, so the flow can be controlled and, thus, the thrust, but they are more complex, and solid rockets, which have the propellants together and they will burn when they are affected by an igniter, but they are simple. [HALL15]

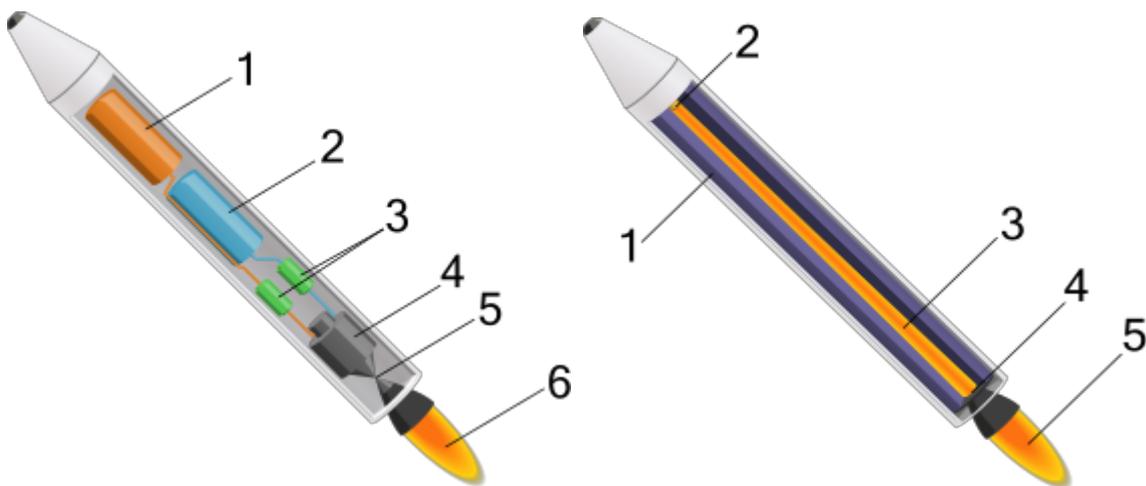


Figure 15: Schematic of a liquid (Left) and a solid (Right) rocket engine [WIKI19RE]

IC engines

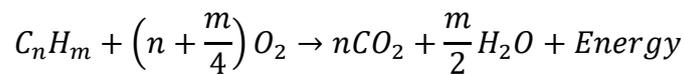
Reciprocating engines will be the subject matter as they are the most common IC engines used.

3. EMISSIONS

3.1. Exhaust composition

Automobiles' work is based on the chemical reaction of an engine which generates the energy that will be transformed into movement. This chemical reaction results in a few products that are transported through the exhaust system to the environment. These products are known as emissions.

Since combustion engines use as reactants oxygen (O_2), coming from the air, and hydrocarbons (C_nH_m), from the fuel, the ideal chemical reaction of a combustion engine should be:



Based on this reaction, the emissions should merely be carbon dioxide (CO_2) and water (H_2O) and they are proportional to molecules of the hydrocarbon, as well as the energy delivered from it. This theoretical process is almost harmless to the environment except if there was an extremely concentration of the exhaust emissions which are considered greenhouse gases [JANI11].

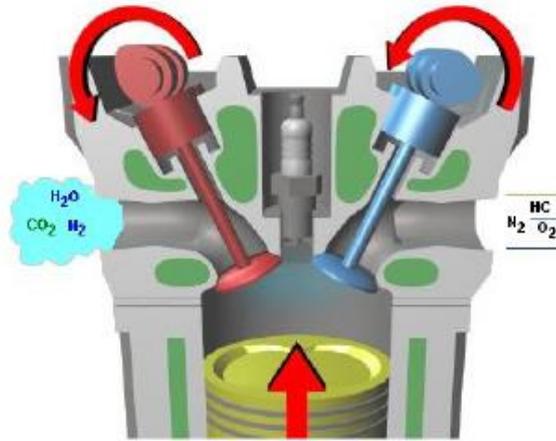


Figure 16: Ideal SI engine combustion process [JANI11]

This ideal reaction is a complete combustion of all the components which means an absolute interaction of all the reactants that cannot be produced through the following reasons [JANI11]:

- Oxygen is not the only component of air: The main component is the nitrogen (N_2) (See Figure 16)
- Fuel is not entirely composed of hydrocarbons and usually they have additives, as AdBlue
- Occasionally oxygen deficiency
- Oil leakage in the combustion chamber

Emissions

- Variations of temperature and pressure in the combustion chamber, for example when the engine has just been started

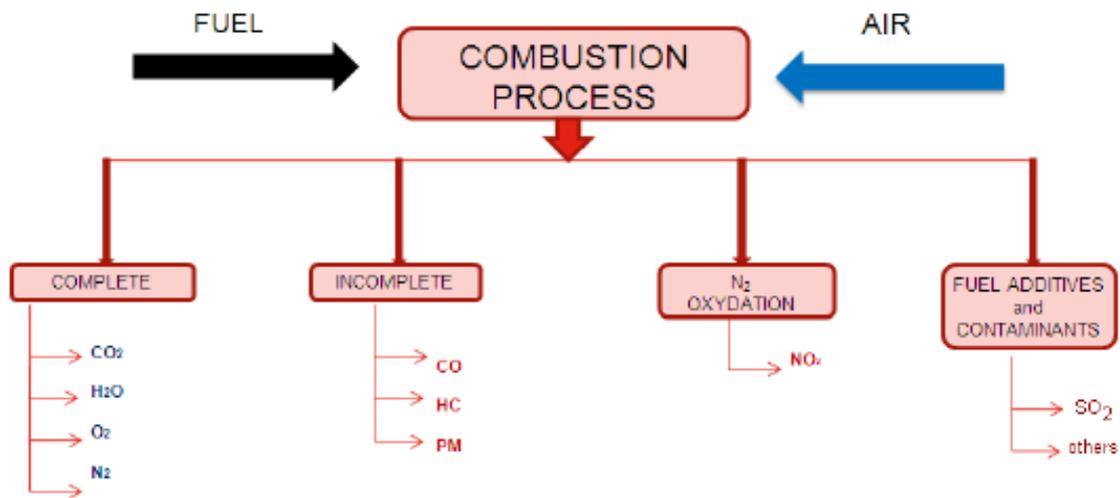


Figure 17: Structure of combustion components depending on how the development of the reaction [JANI11]

Figure 17 presents how the exhaust gases are divided. As already mentioned, the complete combustion of the air-fuel mixture results in non-toxic components which exclusively have the issue of the greenhouse gases that will be discussed in depth later. The incomplete combustion produced by the previously mentioned factors derives in toxic elements that its inhalation can be considered fatal. Nitrogen oxides (NO_x) are especially harmful to the respiratory systems and different methods exist to prevent its appearance. Lastly, the effects of sulfur oxides (SO_x) can be hazardous to the environment when producing acid rain; however, they are needed for the correct engine lubrication.

Furthermore, there are variations in the exhaust gases concentration depending on the fuel type and the combustion process: A spark ignition (SI) engine with gasoline do not produce the same emissions as a compression ignition (CI) one (See *Table 1*).

Table 1: Approximate concentration of toxic exhaust gases from a SI and CI engine [JANI11]

Engine	CO	HC	NO _x	PM
	% vol			mg/m ³
Diesel	0,01 - 0,1	0,005 - 0,5	0,003 - 0,06	20 - 200
Gasoline	0,1 - 6,0	0,5 - 1,0	0,04 - 0,4	1-10

Combining the ideas from the *Figure 17* and *Table 1*, it is observable that the optimum solution should be an equilibrium between automobiles of both engines, with more advantage in number of gasoline engines due to its extremely lower value of particulate matter (PM).

Emissions

Furthermore, there is a relation between the air/fuel ratio and the concentration of hydrocarbons (See *Figure 19*). Its amount has an exponentially increase with a richer mixture, while the optimum value for a minimum production is in a quite leaner mixture (Approximately 17:1; $\lambda > 1$).

The variety of hydrocarbons forms a great number of different compounds as *Figure 20* shows, but the two most important due to its toxicity are:

- Volatile organic compounds (VOCs)
- Polycyclic aromatic hydrocarbons (PAHs)

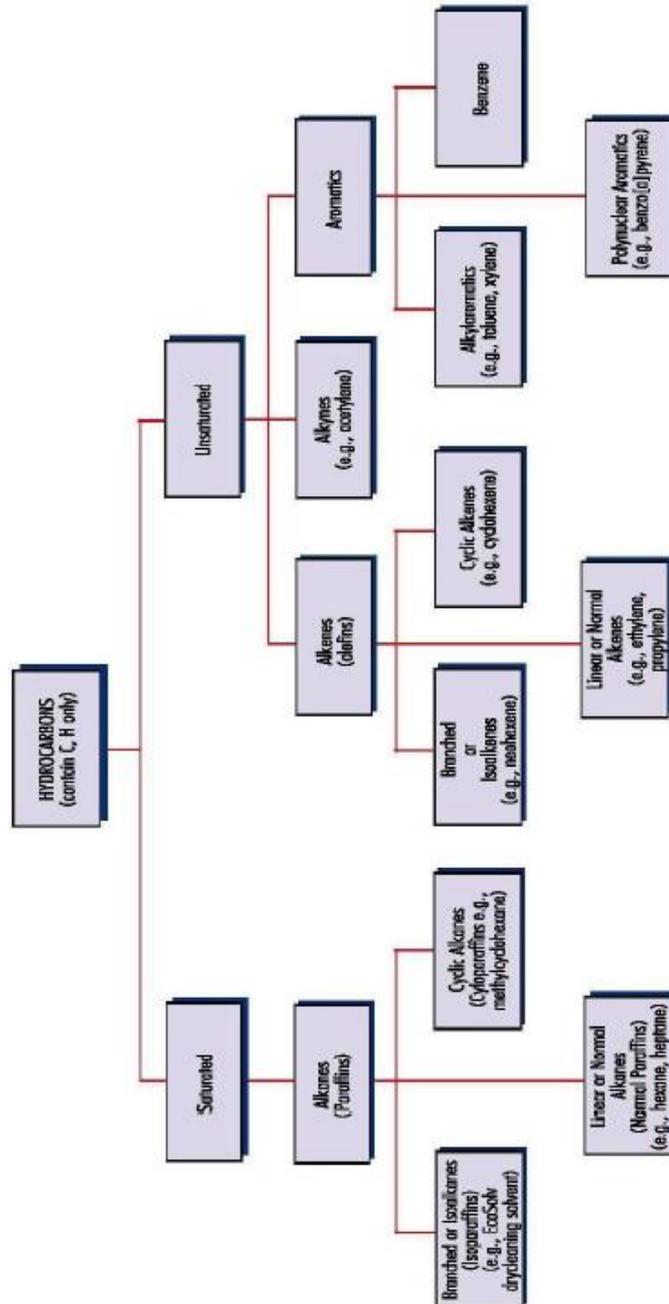


Figure 20: Types of hydrocarbons [JANI11]

3.1.1.1. Volatile organic compounds (VOCs)

The volatile organic compounds are a group of over 200 different compounds existing in the diesel engine exhaust, being the most known: Benzene, formaldehyde and acrolein. Although, they are frequently known as reactive organic gases (ROGs) due to their reaction with NO_x and the sunlight's ultraviolet energy which produces ozone (O_3), different VOCs have not been related to the O_3 formation as they are non-reactive hydrocarbons [JANI11].

These compounds are known for being hazardous to the environment (For contributing to ozone formation in the tropospheric layer, hazardous for living beings, and degrading the one in the stratospheric layer which is the one that protects living beings from ultraviolet light and, also, an input in the greenhouse effect) and the human being too, causing them to accumulate in form of fat or tissues. As already mentioned, amongst every VOC the most common and toxic are [JANI11]:

- Formaldehyde (methanal): It is created when carbon substances are not fully burned. It is considered a mutagenic, hazardous and toxic compound.
- Benzene: In addition, to its mutagenic and carcinogenic properties, it is considered one the most toxic industrial poisons due to its high volatile and commutation ability in the air.
- Acrolein: It can cause eyes and respiratory irritations even in low concentrations and it can even be deadly.

3.1.1.2. Polycyclic aromatic hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons' origin is based on an intense heating process of organic substances and in the case where all hydrocarbons are not fully oxidized apart from methane. These two events occur in a combustion engine that makes them to be identified as one of the principles causes of PAHs emission, especially the CI engines. PAHs are commonly found forming groups in soil, but it is not common in water due to their lack of water-soluble characteristics [JANI11].

Its origin can be in many daily human activities and in the industry while burning fossil fuels, hence they are considered one of the most important organic pollutants. Furthermore, they can be absorbed through the skin, the respiratory system and orally, causing internal damages, diseases and even death. Although, its hazardous effects, only 17 from the over 200 different discovered compounds have been classified as toxic. These harmful elements can be found in the *Table 2* [JANI11].

Emissions

Table 2: Toxic and carcinogenic discovered PAHs [JANI11]

No	Polycyclic aromatic hydrocarbon	Molecular formula	Structural formula	Molecular mass	Boiling point °C
1.	Acenaften	C ₁₂ H ₁₀		154.2	96.2
2.	Acenaftylen	C ₁₂ H ₈		154.2	265-275
3.	Fluoren	C ₁₃ H ₁₀		166.2	295
4.	Antracen	C ₁₄ H ₁₀		178.2	342
5.	Fenantren	C ₁₄ H ₁₀		178.2	340
6.	Fluoranten	C ₁₆ H ₁₀		202.3	375
7.	Piren	C ₁₆ H ₁₀		202.3	404
8.	Chryzen	C ₁₈ H ₁₂		228.3	448
9.	Benzo(a)antracen	C ₁₈ H ₁₂		228.3	437.5
10.	Benzo(a)piren	C ₂₀ H ₁₂		252.3	310-312
11.	Benzo(b)fluoranten	C ₂₀ H ₁₂		252.3	481.2
12.	Benzo(e)piren	C ₂₀ H ₁₂		252.3	492.3
13.	Benzo(k)fluoranten	C ₂₀ H ₁₂		252.3	480
14.	Benzo(j)fluoranten	C ₂₀ H ₁₂		252.3	480
15.	Dibenz(a,h)antracen	C ₂₂ H ₁₄		278.4	269-270
16.	Benzo(g,h,i)perylene	C ₂₂ H ₁₂		276.3	500
17.	Indeno(1,2,3-cd)piren	C ₂₂ H ₁₂		276.3	530

Above all these components, in relation to its harmfulness level, it is benzo[a]pyrene (BaP), that has been considered one of the most important pollutants by the US. Environmental Protection Agency (EPA). BaP is present in water, smoke and sediments and it is created while partially burning sub-products of oil, fossil fuels and organic matter. In high concentrations, it can affect the red blood cell, leading to damages in the immune systems, and, also, causing cancer, which is enhanced by the contact of the skin and sunlight, and damages in internal organs, such as the respiratory system [JANI11].

3.1.2. Carbon monoxide (CO)

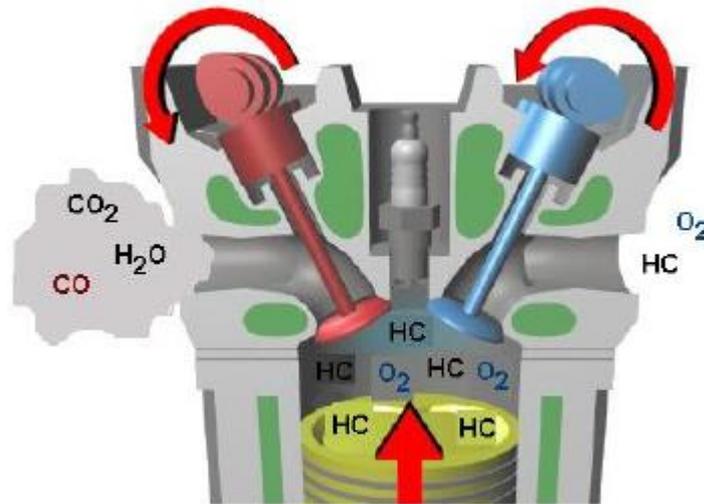


Figure 21: CO creation process in combustion [JANI1]

Carbon monoxide is partially burned fuel and it is specially produced in an environment lacking oxygen that produces a rich combustion (Air/fuel ratio is low; $\lambda < 1$). Consequently, not all carbon atoms are oxidized by oxygen preventing the formation of carbon dioxide (CO_2). The possible causes for this effect are [JANI1]:

- High pressure fuel
- Cold air
- Defective injectors
- While warming the engine

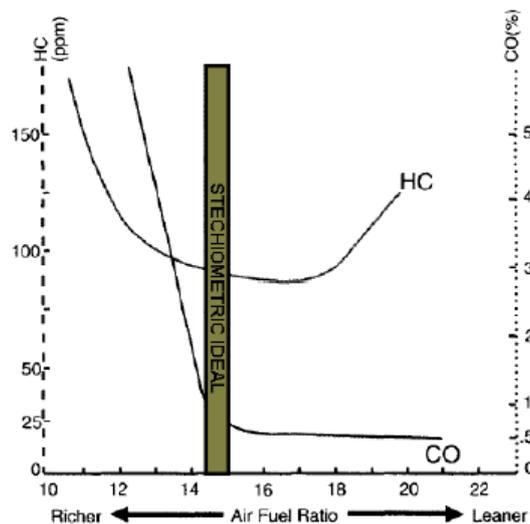


Figure 22: Relation between air /fuel ratio and CO [JANI1]

Comparing the relations of hydrocarbons and carbon monoxide creation with the fuel/air ratio (See Figure 22), carbon monoxide's concentration has a dramatical evolution in a rich mixture as hydrocarbons do, but the lowest value is at the cleanest ratio.

Emissions

3.1.3. Nitrogen oxides (NO_x)

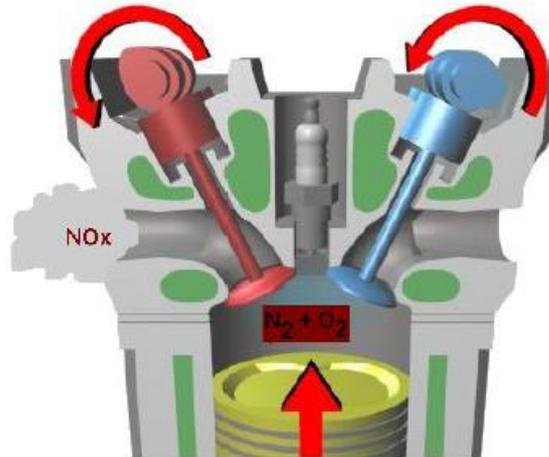


Figure 23: NO_x creation process in combustion [JANI11]

Nitrogen oxides are the result of the oxygen and nitrogen atoms union, which occurs in high pressure and temperature conditions. Even there is a great variety of nitrogen oxides, 98% are nitric oxide (NO). It is created in all types of loading conditions, however it is especially created in heavy load conditions, where temperatures and pressures are higher. Some causes for its creation are [JANI11]:

- Lack of exhaust gases recirculation (EGR) system
- High air/fuel ratio (Lean mixture) (See Figure 24)
- High temperature of intake air
- Poorly refrigerated engine
- High spark advance

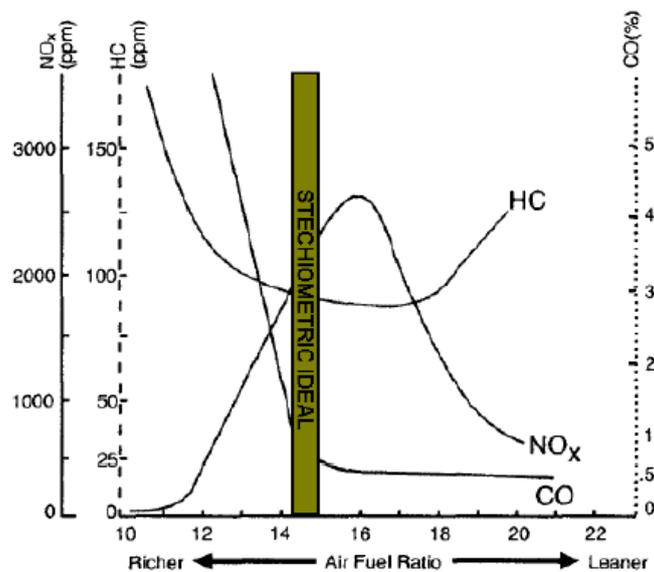


Figure 24: Relation between air /fuel ratio and NO_x [JANI11]

The three last mentioned components are compared in Figure 24 and the air/fuel ratio with lower general emissions is around 17:1, where the value of hydrocarbons is the lowest (Approx. 80 ppm), also, the carbon monoxide's concentration is approximately the lowest (Approx. 5%) and even the nitrogen oxide quantity is not at the minimum

(Approx. 1750 ppm), it forms an acceptable equilibrium between the chemical products. It must be taken into account that the optimal ratio here evaluated has not considered the harmful effects to the environment or the human being.

3.1.4. Sulfur oxides (SO_x)

Sulfur oxides (SO₂ and SO₃) have their origin in the oxidation of sulfur. To prevent them from appearing by reducing the sulfur content in the fuels, since the formation of sulfur oxides is proportional to the concentration of sulfurs in fuels. However, reducing the quantity of sulfur in fuels is expensive and also it works as lubrication for the engine, so it can produce deterioration to the engine's systems [JANI11].

Wet scrubbing is another alternative to reduce sulfur oxides concentration in exhaust gases and in combination to the action of the base engine oil it can be neutralized, as sulfur oxides are corrosive. In this manner it is possible to avoid their combination with moisture to produce acid rain [JANI11].

3.1.5. Particulate Matter (PM) / Soot

Particulate Matter, also called soot, is an association of minuscule elements of solid matter suspended in gas or liquid. It has been analyzed and established that they are created by three mechanisms [JANI11]:

- Nucleus creation
- Nucleus growth and soot molecules formation
- Molecules united to create larger size units

Depending on the engine they can have differences in composition and their properties, but there is a considerable difference in the concentration of particles emitted by spark ignition engines and compressed ignition ones, coming the larger amount of emissions from the last one. Nonetheless, the opacity of the exhaust smoke has nothing to do with the composition of its emissions. The formation causes are the following [JANI11]:

- Union of small uncompleted burned fuel particles
- Partly burned oil
- Fuel oil and lubricant oil containing ash
- Sulphates and water

To classify the different particles, a sized depending system is used (See *Table 3*). This is based on the created term known as aerodynamic diameter, although frequently the particles are not spherical. These dimensions are approximate due to the lack of fully precision of the machines which sizes them.

Emissions

Table 3: Classification of particulate matter based on its aerodynamic diameter size [JANI11]

Fraction	Size range
PM ₁₀ (thoracic fraction)	≤10 μm
PM _{2.5} (respirable fraction)	≤2.5 μm
PM ₁	≤1 μm
Ultrafine (UFP or UP)	≤0.1 μm

3.1.6. Carbon dioxide (CO₂)

Carbon dioxide is the most important greenhouse gas and its origin is, as previously mentioned, in the ideal exothermic reaction of the hydrocarbons of the fuel, containing carbon, with the ideal air, only composed by oxygen. Its concentration can only be reduced by decreasing the fuel consumption [SCHAF95].

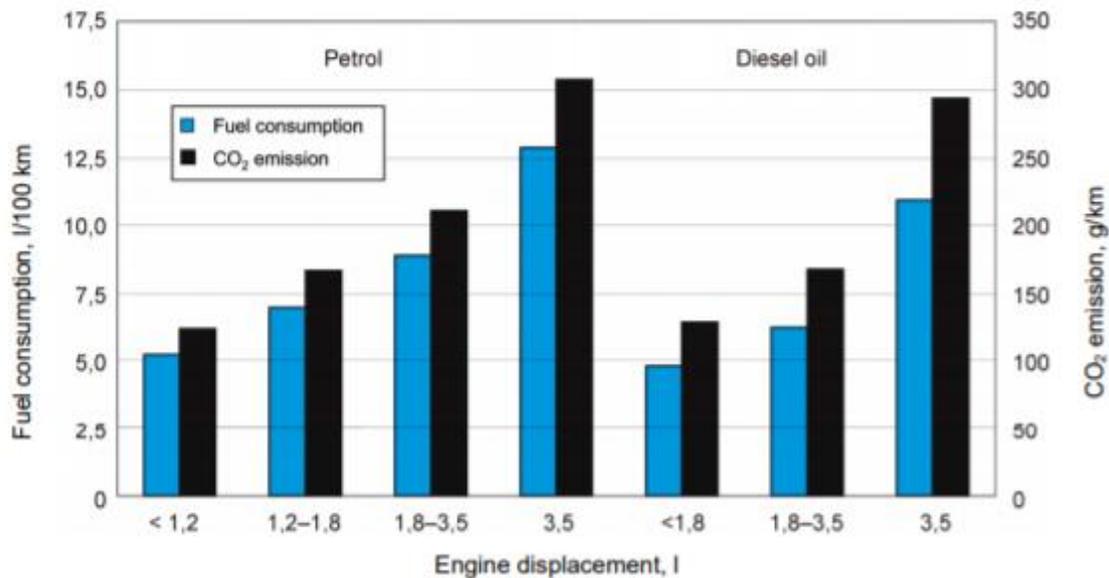


Figure 25: Relation between fuel consumption and carbon dioxide emissions with the fuel used and the engine displacement [MICK07]

From Figure 25, in order to reduce the fuel consumption of an engine the main solutions are the used of more efficiency engine's cycle (Diesel instead of Otto), which can improve the fuel consumption in approx. 30% (approx. 25% of CO₂ emissions), and the reduction of the engine displacement, which directly implies a reduction of the use of fuel up to 60% of decrease (approx. 60% reduction of CO₂ emissions) when considering a gasoline engine of 3.5 l and a 1.2 l. This displacement reduction is represented by the trend known as downsizing, which will be evaluated afterward.

Furthermore, there is a relationship of the air/fuel ratio and the formation of carbon dioxide which can be observed in Figure 26.

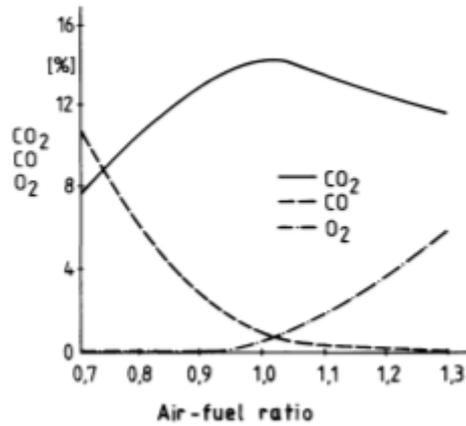


Figure 26: Relationship of air/fuel ratio and carbon dioxide formation [SCHAF95]

A leaner or a richer mixture can result in a reduction of the CO₂ concentration in reference to the stoichiometric mixture where almost all the carbon of the fuel and the oxygen from the air result in CO₂. It must be considered that a leaner or richer mixture implies the production of larger amounts of CO and HC in the combustion chamber, as previously represented in the Figure 24.

3.2. Greenhouse gases

3.2.1. Greenhouse effect

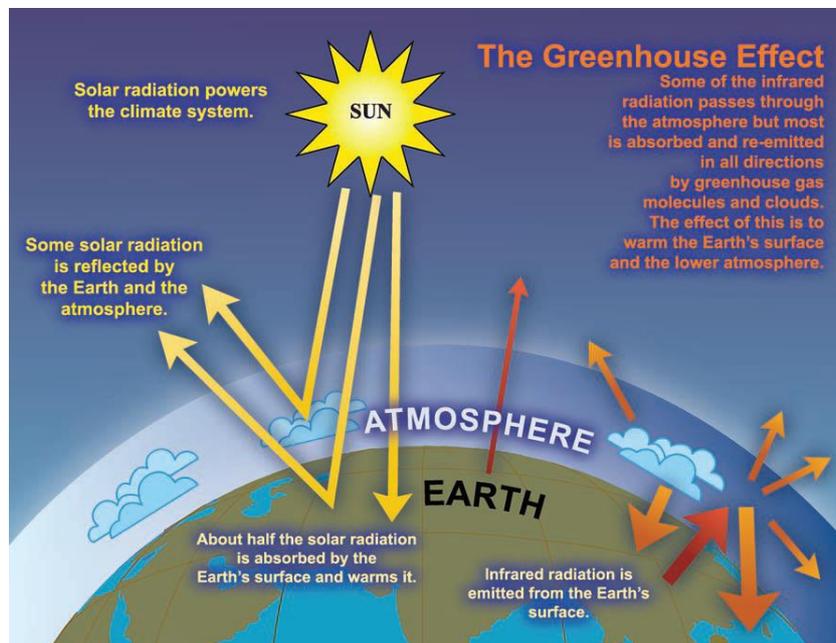


Figure 27: Schematic of the greenhouse effect [SOLO17]

The greenhouse effect is a natural process through which the Earth reaches the actual temperatures by being warmed by the Sun. It is an indispensable effect needed for the existence of life in the Earth because otherwise the Earth would be approximately at the temperature of the moon (-153°C) [LALL18]. The given name is because it shares the

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same working principle as a greenhouse: First, the Sun radiates energy at short wavelength to the Earth (Greenhouse) and the atmosphere absorbs part of it (This share can reach up to two-thirds of the whole energy received); then, to maintain approximately the equilibrium, the land and ocean emit at longer wavelengths (As Earth's temperature is much lower than the Sun's) part of the solar energy that has not been absorbed, which is again absorbed by the atmosphere and redirected to the Earth as before. This amount of radiation that is absorbed back to the atmosphere is because of the concentration of so-called greenhouse gases. [SOLO17]

Above all the existing greenhouse gases, the more important ones are water vapor (H_2O) and carbon dioxide (CO_2). As an interpretation from *Figure 28* both elements, especially H_2O , have an important responsibility in the absorption of radiation among different wavelengths and, as already mentioned, outstanding on the larger ones due to the lower temperature of Earth comparing it to the Sun's one. Their concentrations depend upon a variety of factors from the nature such as plants which absorb CO_2 to be able to do the photosynthesis or human activities, mainly by the burning of fossil fuels and the deforestation. But these direct factors are not the only responsible ones for the effects of the greenhouse gases, in nature there are also some indirect feedback mechanisms that contribute to the warming of the Earth. For example, the water vapor is a greenhouse gas itself and it leads to an increase of temperature, that involves more production of water vapor, which as a result can imply even a double increase in the greenhouse effect. [SOLO17]

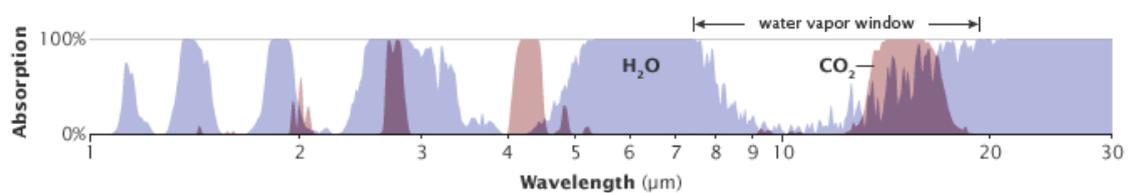


Figure 28: Absorption of different wavelengths by water vapor (H_2O , Blue) and carbon dioxide (CO_2 , Red)
[WIKI19GE]

As already commented, this is a crucial effect for life on Earth, but the problem occurs when there is an overheating of the Earth (See *Figure 29*). The consequence of this abruptly increased of temperatures is known as global warming. For year 2050, the estimated temperature will be around $2^\circ C$ above pre-industrial level and it must be considered that the warming effect in the Arctic is around twice the global average [EEAC19]. Furthermore, the consequence of the melting of the poles which result in the increase of the water level which will derivate in the disappearance of land.

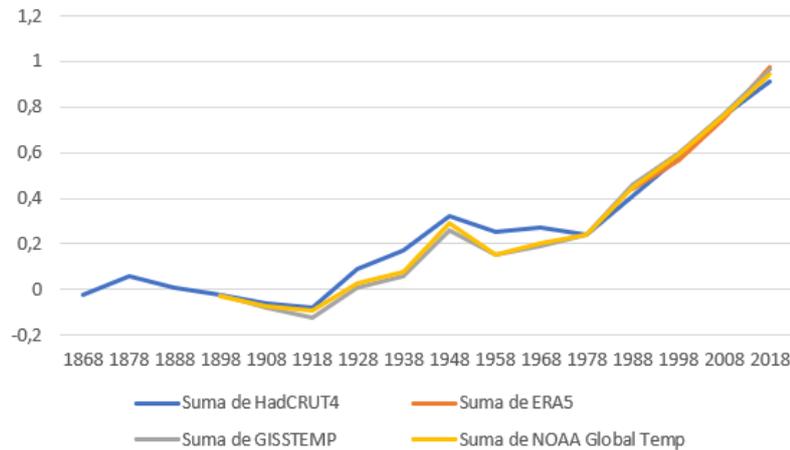


Figure 29: Evolution per decade of the global average near surface temperatures relative to the pre-industrial period [EEAC19GAST]

3.2.2. Greenhouse gases

These gases are the responsible for the greenhouse effect and are located in the atmosphere, absorbing and emitting the radiation contained in the thermal infrared section coming from the top of the Earth, clouds and the atmosphere. Among others, the main greenhouse gases coming from natural and human causes are [SOLO17]:

- Water vapor (H_2O)
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Tropospheric ozone (O_3)
- Fluorinated gases (Sulfur hexafluoride, SF_6 , hydrofluorocarbons, HCFs, and perfluorocarbons, PFCs)

In the study of the greenhouse effect and its relationship with the concentrations of greenhouse gases, a variable that defines the ability to absorb radiation of each of the gases is needed. This term is the radiative forcing (RF, W/m^2). It is the working principle of the greenhouse effect and it is defined, in short terms, as the difference of the solar radiation entering the atmosphere and the radiation leaving it. Thus, if the RF is positive it means that more radiation energy is being received from the Earth that it can emit, which results in an increment of its temperature, if RF is negative, vice versa. The elements or events that produce variations of RF are called radiative forcing mechanisms and not only the greenhouse gases are these mechanisms, but also changes of the Sun production of radiation, the position of the Earth in the Solar System, etc. [CAMP19]

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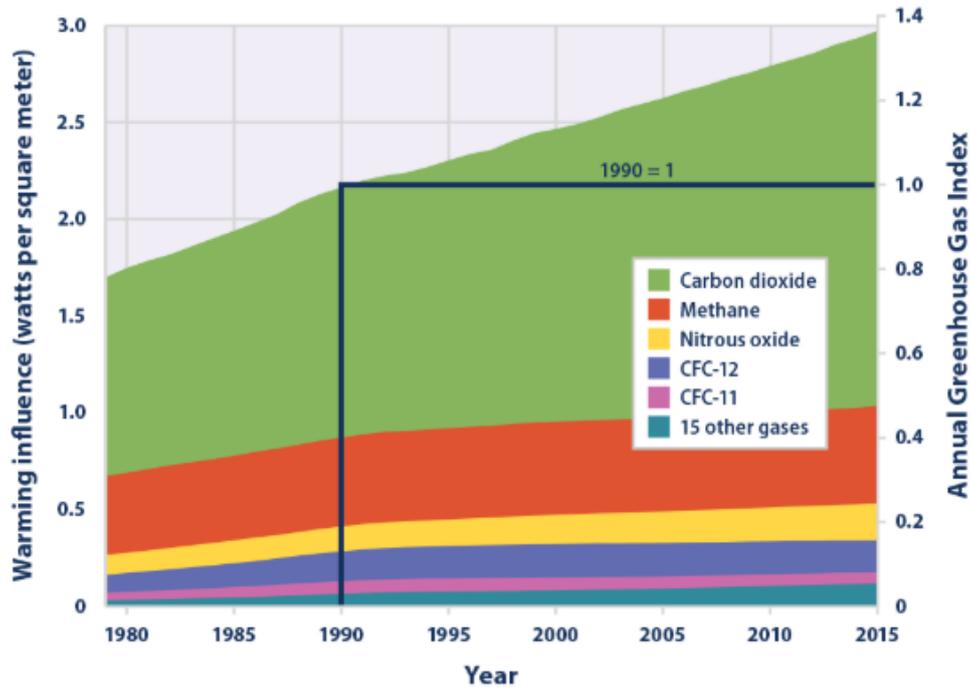


Figure 30: Amount of radiative forcing caused by various greenhouse gases, from 1979 to 2015 [EPA_16]

The Figure 30 represents the evolution over recent years of long-lived greenhouse gases' radiative forcing. These variations are due to the changes in the greenhouse gases concentrations. On the secondary vertical axes, it is represented an index that illustrates the change in percentage of the radiative forcing relative to the value in 1990. As expected, all gases have larger amounts of RF, but especially CO₂'s value has extremely grown.

When comparing different greenhouse gases, it must be considered not only their ability to absorb the radiating energy (Radiative forcing), but also the time that they will last in the atmosphere (Lifetime) and both variables are combined in the parameter known as Global Warming Potential (GWP). This coefficient measures the quantity of energy that 1 ton of gas is able to absorb in a certain time (Commonly, 100 years), based on the same effect of 1 ton of carbon dioxide. The GWP parameter not only consider the direct effect of this gases on absorbed radiation, but also the indirect effect of them, as CH₄ that is the antecedent of O₃ which is considered a greenhouse gas. Thus, there are different values for GWP coefficient due to the variety of calculation forms for different considerations of the greenhouse gas influence [EPA_17].

Table 4: Radiative forcing, lifetime and Global Warming Potential values for main long-lived greenhouse gases or the year 2015 [EPA_16] [EPA_17] [EPA_19]

Compound	RF (W/m ²)	Lifetime (years)	GWP
CO ₂	2,9	>1000	1
CH ₄	0,9	12	25
N ₂ O	0,4	114	298
Fluorinated gases	0,2	270-50000	7.390-22.800

To compare the influence of these gases in the greenhouse effect the data about RF, lifetime and GWP from the main greenhouse gases is resumed in *Table 4*. As expected, the CO₂, even having less GWP their extremely high concentration results in a great absorption ability resumed in the value of RF. Although, the carbon dioxide's lifetime is established to be more than 1000 years, it is actually difficult to determine it due to the great number of sources and sinks of this compound.

3.2.2.1. Water vapor (H₂O)

Water vapor is the most predominant greenhouse gas filling the 90% (approx.) of the total volume of all the gases and being up to 85% responsible of the entire greenhouse effect. However, even its high influence, the water vapor is not the real problem in the enhanced effect. Among other reasons, the water vapor has a low lifetime (Rapid water cycle, around 10 days), its saturation vapor pressure that limits its quantity and, most important, the exceptionally high thermal inertia of the Earth due to the enormous proportion of water over land in it (Approx. 66% of water), that avoid the rapid change of temperatures in the short time with normal conditions [HAUS08].

The real problem that the water produces is owing to its feedback loop phenomena. This consists in the evaporation of more quantity of water due to the higher temperatures produced by all the greenhouse gases, resulting in an even greater concentration of it. Furthermore, the warmer the air is, the higher is its absolute humidity, thus, more water vapor can form part of the atmosphere. In addition, the warmer environment affects in the cloud's formation deriving in a higher increase of temperature of the Earth. Unlike water, long-lived greenhouse gases result in a constant warmer environment escalating this effect due to its longer lifetime. An estimation of this feedback mechanism has been studied and it establishes that this effect produces up to a 30% higher temperature than it would be without it [HAUS08].

3.2.2.1. Carbon dioxide (CO₂)

Even it is not the most abundant gas, carbon dioxide is the most important greenhouse gas due to its consequences and its increasing concentration. Its origin is in the result of both human activities and natural processes that constitute the carbon cycle of the Earth, consisting in the carbon circulation through the atmosphere, land, oceans, animals and trees. CO₂'s concentration used to balance itself by been produced and absorbed by natural processes developed by living beings. The problem began with the First Industrial Revolution back in 1750, when as a result of human activities there was not only an increase in its emissions but an alteration in the natural mechanisms of reducing it such as forests [EPA_19].

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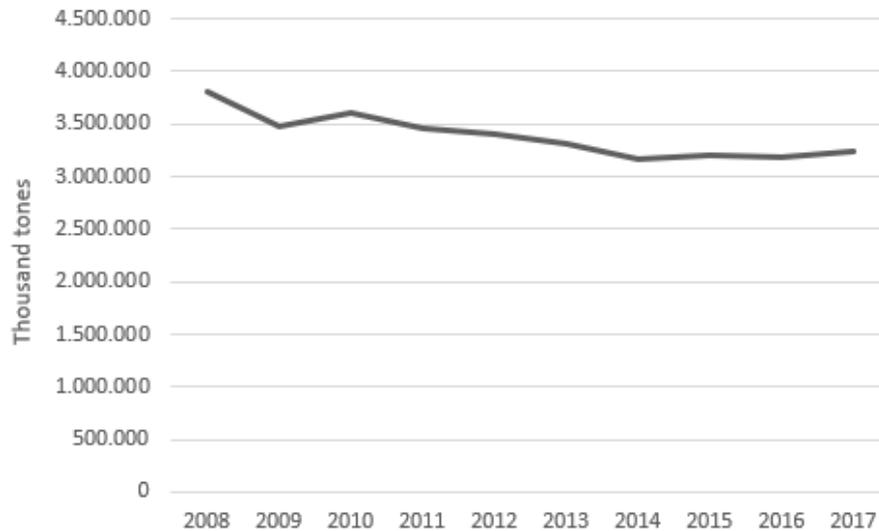


Figure 31: Carbon dioxide's emissions evolution in Europe from 2008 to 2017 [EURO19GHGESS]

In relationship to the trend of emissions of carbon dioxide in Europe (See *Figure 31*), there is a clear decrease over the last decade and in the year 2019 the CO₂ emissions are expected to be just above 3.000.000 thousand tones, meaning an overall decrease of approx. 20%.

3.2.2.1. Methane (CH₄)

Methane has its origin in natural sources such as oceans, volcanoes, wildfires, animal waste and, especially, wetlands, where bacteria produce anaerobically it when decomposing organic matter, but also it is a consequence of natural gas' leakages and the excessive increase of livestock. On the other hand, natural mechanism of soil and chemical reactions help to reduce the concentration of the same [EPA_19].

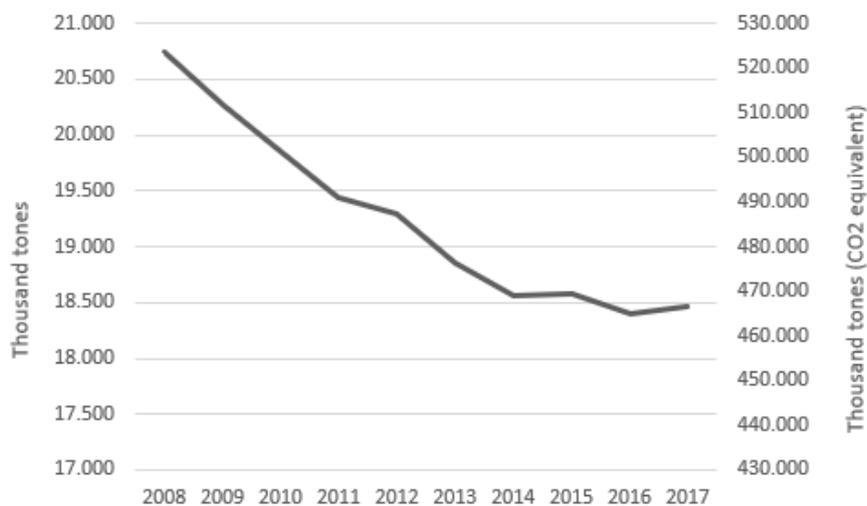


Figure 32: Methane's emissions evolution in Europe from 2008 to 2017 [EURO19GHGESS]

The evolution of the methane’s emissions has been decreasing in the last decade (approx. 10%) and it is expected to be around 18.500 thousand tones. In its relation to the CO₂’s effect, it was approx. 85% less effective in the year 2017.

3.2.2.2. Nitrous oxide (N₂O)

Nitrous oxide is a greenhouse gas mainly originated in natural sources that constitute the nitrogen cycle such as animals, plants and microorganisms present in soils and oceans. But also, there are natural mechanisms that reduce its concentration like bacteria, ultraviolet radiation or some chemical reactions that destroy or break down the nitrogen compounds [EPA_19].

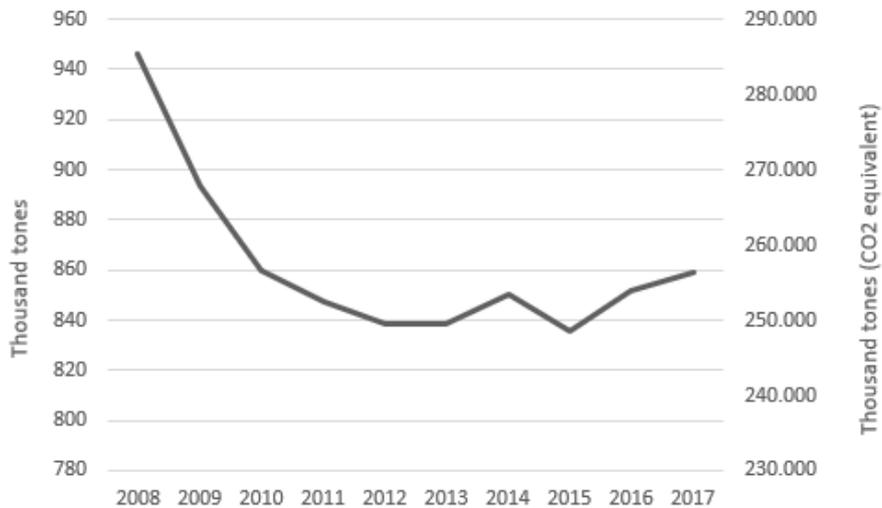


Figure 33: Nitrous oxide's emissions evolution in Europe from 2008 to 2017 [EURO19GHGESS]

The Figure 32 represents the nitrous oxide’s emissions trend and shows that the in the year 2019 they will be around 850 thousand tonnes which is a decrease of approx. 10%. Furthermore, the figure represent these emissions in relation to the effect of CO₂, which present that the overall effect of the nitrous oxide’s emissions is 92% less effective, even of its higher potency.

3.2.2.3. Tropospheric ozone (O₃)

Ozone has its origin in the reaction of gases, such as carbon monoxide, methane or hydrocarbons and nitrogen oxides coming from vehicles emissions, with the sunlight and it has a lifetime of few weeks. This gas is not only responsible of part of the greenhouse gas but also it is harmful for respiratory systems of living beings, thus, depending on the altitude of its concentration it would be beneficial (Ozone layer) or harmful for the environment (Tropospheric ozone) [AFEW18].

In addition to its short lifetime and as ozone can be harmful or beneficial for the environment based on its altitude, it is difficult to obtain data of the ozone that influences the greenhouse effect [EEAC15APO].

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3.2.2.4. Fluorinated gases

Fluorinated gases are completely human activities's originated and they are considered the most effective and with more lifetime of all the non-natural gases emitted. Thus, short amounts of them are considered extremely effective as greenhouse gases. They are used instead of substances that reduce the ozone layer such as refrigerants, solvents or fire retardants, in the industry when producing aluminium or in other semiconductor manufacturing and in electrical equipment as insulating gas. The almost unique reduction mechanism for these gases is the sunlight inciding in the upper part of the atmosphere [EPA_19].

Although, their effect in the greenhouse effect is extremely high, their concentrations are quite modest, so they are commonly compared with the influence of carbon dioxide in the greenhouse effect.

3.2.3. Anthropogenic and non-anthropogenic theories

When trying to find the responsible for these emissions, the origins must be divided into human activities causes (Anthropogenic causes) and natural causes (Non-anthropogenic causes).

3.2.3.1. Anthropogenic causes

This section includes every source of emissions produced by the result of human activities [EUCC14] [BODE09]:

- Burning fossil fuels: From the First Industrial Revolution in the 18th century, carbon dioxide emissions from burning fossil fuels like coal, oil and natural gas have been increasing over the centuries in order to mainly produce electricity and for transportation. The possible solution is the application of alternative sources as solar energy.
- Deforestation: Plants contribute to the diminution of carbon dioxide through the photosynthesis and humans have been decreasing the number of trees to create new living places and for burning purpose.
- Increasing livestock: Naturally human and animals produce methane as a result of the digestive process, but the increasing number of animals due to enhance breeding of animals from humans for food objectives has turned it into a problem.
- Fertilizers containing nitrogen
- Fluorinated gases: Aerosols are produced from fossil fuel combustion and they are used in refrigeration systems which production is rising over time.
- Industrial waste and landfills: Cement production, coal related activities and landfills of garbage result in the emissions of various greenhouse gases

3.2.3.2. Non-Anthropogenic causes

As already mentioned, the greenhouse effect is a natural process, thus there must be some non-anthropogenic causes for it [HEC_]:

- Solar radiation: The Sun is partially covered by sunspots. This is a cyclical process that last from 11 to 22 years and it affects the solar radiation received by the Earth on approx. 0,1%, so it cannot be the responsible of the Earth's temperatures changes.
- Volcanoes: These natural events emit large amounts of emissions, including carbon dioxide, but also particulates that prevent the solar radiation from reaching the Earth surface, producing a considerable decrease of the Earth's temperatures.
- Earth's orbit: The effect of the distance from the Sun to the Earth it is a parameter conditioning its temperature and this event was described by Milutin Milankovitch declaring that the causes of this variations where the eccentricity (Distance from the Sun to the Earth's orbit), obliquity (Inclination of the Earth respect to its vertical axis) and precession (The oscillation of the Earth's vertical axis)

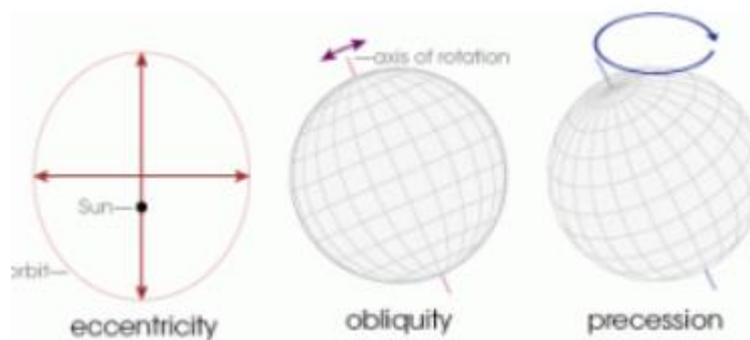


Figure 34: Earth's changes in orbit according to Milutin Milankovitch [HEC_]

- Oceans: Oceans accounts approx. 70% of the Earth's extension and due to the water's high specific heat they accumulated up to 90% of the increase of energy from 1971 to 2010.

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4. DOWNSIZING

4.1. Definition

In a few words, downsizing is a technic used to increase the efficiency of an engine by reducing its general displacement, which would produce a loss of effectiveness, in combination with innovative technologies, such as forced induction, to increase the power balancing the overall performance. Through this achievement it is a more efficient and, thus, less contaminant machine. In comparison with a larger engine, the improvement is represented by the reduction of the engine's size maintaining the technical specifications of power and torque, resulting in an improvement of the volumetric efficiency.

Moreover, not only the volumetric efficiency is upgraded, but also the weight, the dimensions, friction and thermal losses of the engine are reduced resulting in a notorious advance. However, to achieve this development some aspects must be considered such as building a powerful enough combustion system and engine block and having the considerable low speed torque and a progressive evolution [SUWA15].

Table 5: Committee's Estimates of Effectiveness as a percentage [NRC_11]

Technologies		Incremental values - A preceding technology must be included								
		I4			V6			V8		
Technologies	Abbreviation	Low	High	AVG	Low	High	AVG	Low	High	AVG
Spark Ignition Techs										
Low Friction Lubricants	LUB	0.5	0.5	0.6	0.5	0.5	0.6	0.5	0.5	0.6
Engine Friction Reduction	EFR	0.5	2.0	1.3	0.5	2.0	1.3	1.0	2.0	1.6
VVT- Coupled Cam Phasing (CCP), SOHC	CCP	1.5	3.0	2.3	1.5	3.5	2.6	2.0	4.0	3.0
Discrete Variable Valve Lift (DVVL), SOHC	DVVL	1.5	3.0	2.3	1.5	3.0	2.3	2.0	3.0	2.6
Cylinder Deactivation, SOHC	DEAC	NA	NA	NA	4.0	6.0	6.0	5.0	10.0	7.6
VVT- In take Cam Phasing (ICP)	ICP	1.0	2.0	1.6	1.0	2.0	1.6	1.5	2.0	1.8
VVT- Dual Cam Phasing (DCP)	DCP	1.5	2.5	2.0	1.5	3.0	2.3	1.5	3.0	2.3
Discrete Variable Valve Lift (DVVL), DOHC	DVVL	1.5	3.0	2.3	1.5	3.5	2.6	2.0	4.0	3.0
Continuously Variable Valve Lift (CVVL)	CVVL	3.5	6.0	4.8	3.5	6.5	6.0	4.0	6.5	6.3
Cylinder Deactivation, OHV	DEAC	NA	NA	NA	4.0	6.0	6.0	5.0	10.0	7.6
VVT- Coupled Cam Phasing (CCP), OHV	CCP	1.5	3.0	2.3	1.5	3.5	2.6	2.0	4.0	3.0
Discrete Variable Valve Lift (DVVL), OHV	DVVL	1.5	2.5	2.0	1.5	3.0	2.3	2.0	3.0	2.6
Stoichiometric Gasoline Direct Injection (GDI)	SGDI	1.5	3.0	2.3	1.5	3.0	2.3	1.5	3.0	2.3
Turbocharging and Downsizing	TRBDS	2.0	5.0	3.6	4.0	6.0	6.0	4.0	6.0	6.0
Diesel Techs										
Conversion to Diesel	DBL	15.0	35.0	26.0	15.0	35.0	26.0	NA	NA	NA
Conversion to Advanced Diesel	ADBL	7.0	13.0	10.0	7.0	13.0	10.0	22.0	38.0	30.0
Electrification/Accessory Techs										
Electric Power Steering (EPS)	EPS	1.0	3.0	2.0	1.0	3.0	2.0	1.0	3.0	2.0
Improved Accessories	IACC	0.5	1.5	1.0	0.5	1.5	1.0	0.5	1.5	1.0
Higher Voltage/Improved Alternator	HVIA	0.0	0.5	0.3	0.0	0.5	0.3	0.0	0.5	0.3
Transmission Techs										
Continuously Variable Transmission (CVT)	CVT	1.0	7.0	4.0	1.0	7.0	4.0	1.0	7.0	4.0
5-spd Auto. Trans. w/ improved Internals		2.0	3.0	2.6	2.0	3.0	2.6	2.0	3.0	2.6
6-spd Auto. Trans. w/ improved Internals		1.0	2.0	1.6	1.0	2.0	1.6	1.0	2.0	1.6
7-spd Auto. Trans. w/ improved Internals			2.0	2.0		2.0	2.0		2.0	2.0
8-spd Auto. Trans. w/ improved Internals			1.0	1.0		1.0	1.0		1.0	1.0
6/7/8-spd Auto. Trans. w/ improved Internals	NAUTO	3.0	8.0	6.6	3.0	8.0	6.6	3.0	8.0	6.6
6/7-spd DCT from 4-spd AT	DCT	6.0	9.0	7.6	6.0	9.0	7.6	6.0	9.0	7.6
6/7-spd DCT from 6-spd AT	DCT	3.0	4.0	3.6	3.0	4.0	3.6	3.0	4.0	3.6
Hybrid Techs										
12V BAS Micro-Hybrid	MHEV	2.0	4.0	3.0	2.0	4.0	3.0	2.0	4.0	3.0
Integrated Starter Generator	ISG	29.0	39.0	34.0	29.0	39.0	34.0	29.0	39.0	34.0
Power Split Hybrid	PSHEV	24.0	50.0	37.0	24.0	50.0	37.0	24.0	50.0	37.0
2-Mode Hybrid	2MHEV	25.0	45.0	36.0	25.0	45.0	36.0	25.0	45.0	36.0
Plug-in hybrid	PHEV	NA	NA	NA	NA	NA	NA	NA	NA	NA
Vehicle Techs										
Mass Reduction - 1%	MR1		0.3	0.3		0.3	0.3		0.3	0.3
Mass Reduction - 2%	MR2		1.4	1.4		1.4	1.4		1.4	1.4
Mass Reduction - 5%	MR5	3.0	3.5	3.3	3.0	3.5	3.3	3.0	3.5	3.3
Mass Reduction - 10%	MR10	6.0	7.0	6.6	6.0	7.0	6.6	6.0	7.0	6.6
Mass Reduction - 20%	MR20	11.0	13.0	12.0	11.0	13.0	12.0	11.0	13.0	12.0
Low Rolling Resistance Tires	ROLL	1.0	3.0	2.0	1.0	3.0	2.0	1.0	3.0	2.0
Low Drag Brakes	LDB		1.0	1.0		1.0	1.0		1.0	1.0
Aero Drag Reduction 10%	AERO	1.0	2.0	1.6	1.0	2.0	1.6	1.0	2.0	1.6

Downsizing

Table 6: Committee's Estimates of Technology Costs in U.S. Dollar in 2009 [NRC_11]

Technologies		NRC 2009 Costs											
		Incremental Values - A preceding technology must be included											
Spark Ignition Techs	Abbreviation	I4				V6				V8			
		Low	High	AVG	AVG w/1.5 RPE	Low	High	AVG	AVG w/1.5 RPE	Low	High	AVG	AVG w/1.5 RPE
Low Friction Lubricants	LUB	3	5	4	6	3	5	4	6	3	5	4	6
Engine Friction Reduction	EFR	32.0	52.0	42	63	48	76	63	94.5	64	104	84	126
VVT - Coupled Cam Phasing (CCP), SOHC	CCP	35		35	52.5	70		70	105	70		70	105
Discrete Variable Valve Lift (DVVL), SOHC	DVVL	130	160	145	217.5	180	210	195	292.5	280	320	300	450
Cylinder Deactivation, SOHC	DEAC	NA	NA	NA	NA	340	400	370	555	357	420	388.5	582.75
VVT - In-take Cam Phasing (ICP)	ICP	35		35	52.5	70		70	105	70		70	105
VVT - Dual Cam Phasing (DCP)	DCP	35		35	52.5	70		70	105	70		70	105
Discrete Variable Valve Lift (DVVL), DOHC	DVVL	130	160	145	217.5	180	220	200	300	280	300	280	420
Continuously Variable Valve Lift (CWVL)	CWVL	150	205	182	273	290	310	300	450	350	390	370	555
Cylinder Deactivation, OHV	DEAC	NA	NA	NA	NA	220	250	235	352.5	255		255	382.5
VVT - Coupled Cam Phasing (CCP), OHV	CCP	35		35	52.5	35		35	52.5	35		35	52.5
Discrete Variable Valve Lift (DVVL), OHV	DVVL	130	160	145	218	210	240	225	338	280	320	300	450
Stoichiometric Gasoline Direct Injection (GDI)	SGDI	117	195	156	234	169	256	213	319	295	351	323	485
Turbocharging and Downsizing	TRBDS	370	490	430	645	-144	205	31	46	525	790	658	988
Diesel Techs													
Conversion to Diesel	DSL	2154	2632	2393	3590	2857	3491	3174	4761	NA	NA	NA	NA
Conversion to Advanced Diesel	ADSL	520	520	520	780	663	663	663	1025	3513	4293	3903	5855
Electrification/Accessory Techs													
Electric Power Steering (EPS)	EPS	70	120	95	143	70	120	95	143	70	120	95	143
Improved Accessories	IACG	70	90	80	120	70	90	80	120	70	90	80	120
Higher Voltage Improved Alternator	HVA	15	55	35	53	15	55	35	53	15	55	35	53
Transmission Techs													
Continuously Variable Transmission (CVT)	CVT	150	170	160	240	243	263	253	380	243	263	253	380
8-spd Auto. Trans. w/ Improved Internals		133		133	200	133		133	200	133		133	200
6-spd Auto. Trans. w/ Improved Internals		133	215	174	262	133	215	174	262	133	215	174	262
7-spd Auto. Trans. w/ Improved Internals		170	300	235	353	170	300	235	353	170	300	235	353
8-spd Auto. Trans. w/ Improved Internals		425		425	638	425		425	638	425		425	638
6/7 & Speed Auto. Trans. with Improved Internals	NAUTO	137	425	281	422	137	425	281	422	137	425	281	422
6/7-spd DCT from 6-spd AT	DCT	-147	185	19	29	-147	185	19	29	-147	185	19	29
6/7-spd DCT from 4-spd AT	DCT	-14	400	193	290	-14	400	193	290	-14	400	193	290
Hybrid Techs													
12V BAS Micro-Hybrid	MHEV	450	550	500	665	585	715	650	865	720	880	800	1064
Integrate d Starter Generator	ISG	1760	2640	2200	2928	2000	3000	2500	3325	3000	4800	4000	5320
Power Split Hybrid	PSHEV	2708	4062	3385	4502	3120	4680	3900	5187	4000	6000	5000	6650
2-Mode Hybrid	2MHEV	5200	7800	6500	8645	5200	7800	6500	8645	5200	7800	6500	8645
Series PHEV 40	PHEV	8000	12000	10000	13300	9600	14400	12000	15960	13600	20400	17000	22610
Vehicle Techs													
Mass Reduction - 1%	MR1	37	45	41	61	45	56	53	80	68	82	75	113
Mass Reduction - 2%	MR2	77	93	85	127	100	121	111	166	142	170	156	234
Mass Reduction - 5%	MR5	217	260	239	358	283	339	311	467	399	479	433	639
Mass Reduction - 10%	MR10	520	624	572	859	679	815	747	1120	955	1150	1054	1561
Mass Reduction - 20%	MR20	1000	1200	1100	1615	1260	1500	1360	2350	1900	2250	1750	2525
Low Rolling Resistance Tires	ROLL	30	40	35	53	30	40	35	53	30	40	35	53
Aero Drag Reduction 10%	AERO	40	50	45	68	40	50	45	68	40	50	45	68

Analyzing the data from the *Table 5* and *Table 6* of a common inline 4-cylinder engine, the technologies frequently related to a downsizing are cylinder deactivation, continuously variable lift and turbocharging and these can be compared to the plug-in hybrid technology. Although, hybrid vehicles have been optimized in the recent years and the cost and technologies have been improved since 2009, also downsizing innovations have been developed and upgraded, thus both alternatives can be compared. While the combination of downsizing results in an efficiency improvement of approximately 13% and a cost of less than 1000\$, the PHEV increments the cost up to 1000% and the maintenance or repairs must be added also and the increment of efficiency is difficult to estimate, nevertheless Toyota, one of the most referring hybrid vehicles companies, declares in its website a fuel efficiency up to 30% in 2019. Even so, downsizing and hybridization are two compatible technologies.

There are few reasons for downsizing to be one of the alternatives for the future of motor vehicles:

- Low-cost solution comparing to others
- Less complex system with technologies that already exist
- The need of reducing fuel consumption and emissions of combustion engines in order to comply the European emission standards (See *Table 7* and *Table 8*)

Table 7: Progression of European emission standards of gasoline engines (g/km) [ECO119CLT] [WIKI19EES]

European emission standards	CO	HC	VOC	NOx	HC+Nox	PM
Euro 1 (July 1992)	2,72	0	0	0	0,97	0
Euro 2 (January 1996)	2,2	0	0	0	0,5	0
Euro 3 (January 2000)	2,3	0,2	0	0,15	0	0
Euro 4 (January 2005)	1	0,1	0	0,08	0	0
Euro 5a (September 2009)	1	0,1	0,068	0,06	0	0,005
Euro 5b (September 2011)	1	0,1	0,068	0,06	0	0,0045
Euro 6b (September 2014)	1	0,1	0,068	0,06	0	0,0045
Euro 6c (-)	1	0,1	0,068	0,06	0	0,0045
Euro 6d (January 2020)	1	0,1	0,068	0,06	0	0,0045
Euro 6d-Temp (September 2017)	1	0,1	0,068	0,06	0	0,0045

Table 8: Progression of European emission standards of diesel engines (g/km) [ECO119CLT] [WIKI19EES]

European emission standards	CO	HC	VOC	NOx	HC+Nox	PM
Euro 1 (July 1992)	2,72	0	0	0	0,97	0,14
Euro 2 (January 1996)	1	0	0	0	0,7	0,08
Euro 3 (January 2000)	0,66	0	0	0,5	0,56	0,05
Euro 4 (January 2005)	0,5	0	0	0,25	0,3	0,025
Euro 5a (September 2009)	0,5	0	0	0,18	0,23	0,005
Euro 5b (September 2011)	0,5	0	0	0,18	0,23	0,0045
Euro 6b (September 2014)	0,5	0	0	0,08	0,17	0,0045
Euro 6c (-)	0,5	0	0	0,08	0,17	0,0045
Euro 6d (January 2020)	0,5	0	0	0,08	0,17	0,0045
Euro 6d-Temp (September 2017)	0,5	0	0	0,08	0,17	0,0045

From *Table 7* and *Table 8*, the percentages of reduction are, for example, 63% of CO in a gasoline engine or 97% of PM and 84% of NO_x in a diesel engine. These data show how strict the laws have come about transport emissions.

Not only these emissions have been limited but also the CO₂ ones [ECO119GHG]:

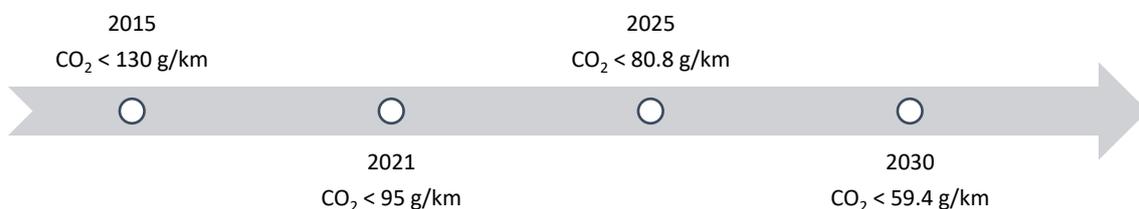


Figure 35: Timeline of CO₂ objective from 2009 to 2030 established by the European Commission [ECO119GHG]

- 2009-2015: The regulation settled the objective of CO₂ emissions by 130 g/km in 2015 employing vehicle technology, but also another emission reduction of 10 g/km with alternative innovations as biofuel, and by 95 g/km in 2020.

Downsizing

- 2015-2021: By the year 2020, 95% of vehicles must meet the emission goal of 95 g/km and 100% of them at the year 2021.
- 2021-2030: New limits of CO₂ emissions have been established, 15% of reduction by the year 2025 (80.8 g/km) and 37.5% by 2030 (59.4 g/km), taking as a reference the data of the year 2021.

In order to meet the established standards, the power density must be enhanced and the only two possible methods are increasing the engine speed or the mean effective pressure as the power density is defined as [GOLLO05]:

$$\frac{P_e}{V_H} = i \cdot n \cdot p_{me} = 2\pi \cdot n \cdot \frac{M}{V_H}$$

Where P_e = Engine's power, V_H = Piston displacement, i = Number of cycles per crankshaft rotation, n = Engine's speed, p_{me} = engine's effective pressure and M = Torque.

This is the key of the downsizing technic and it is represented in *Figure 36*.

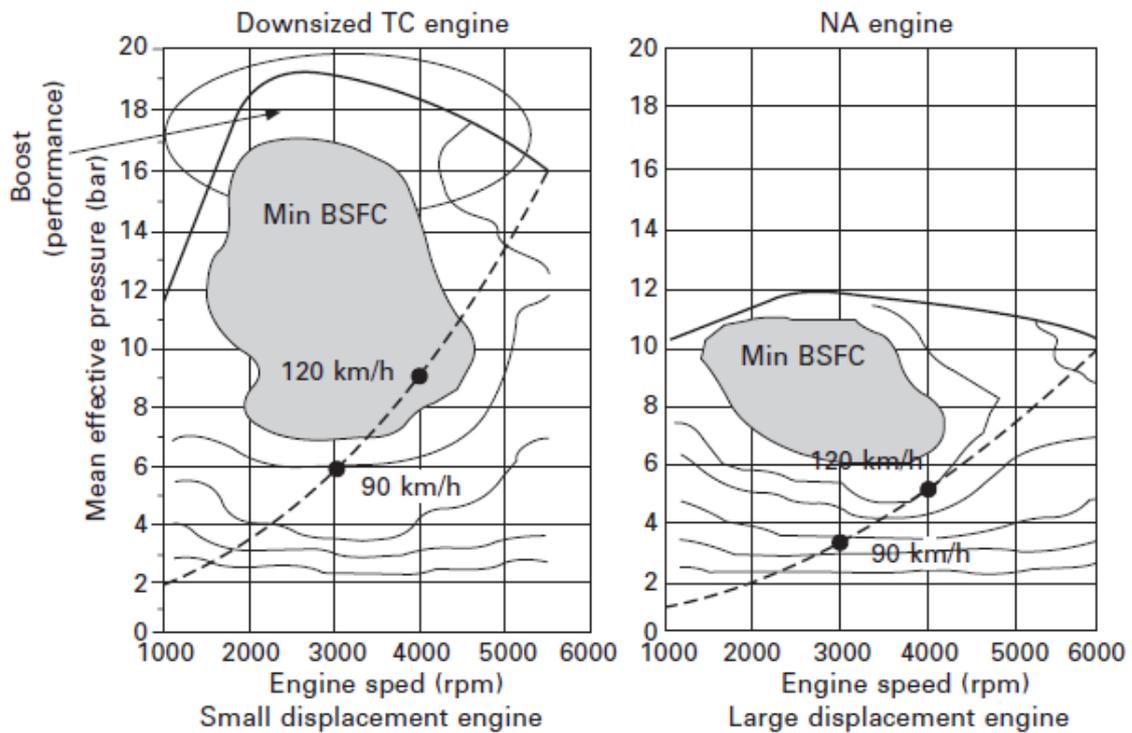


Figure 36: Comparison between a downsized TC engine and NA engine in aspect of mean effective pressure over different engine speed [ZHAO10]

The main difference between a natural aspirated engine and a downsized's one is that the area of the minimum brake specific fuel consumption (BSFC) includes the most common speeds of a vehicle in order to have the minimum fuel consumption in the larger possible share of the engine use. This is achieved by maximizing the brake mean effective pressure (BMEP), which can imply the knocking effect when having maximum torque at low speeds or an eventually break of the turbine due to the higher exhaust's temperatures. If needed, adding a short amount of extra fuel can solve these problems [ZHAO10].

4.2. Methods of downsizing

The principle of downsizing is the reduction of the engine dimensions which leads to a general diminution of its displacement. This is the total volume of all the cylinders between the top dead center (TDC) and the bottom dead center (BDC) (See *Figure 37*). These dimensions are mainly related to the piston displacement or swept volume and the engine capacity, and these variables can be expressed as:

$$V = \frac{\pi d^2 L}{4000} \qquad V_e = \frac{Vn}{1000}$$

Where V = piston displacement (cm^3), d = cylinder diameter or bore (mm), L = cylinder stroke (mm), V_e = engine cylinder capacity (cm^3) and n = number of cylinders [CROL09]

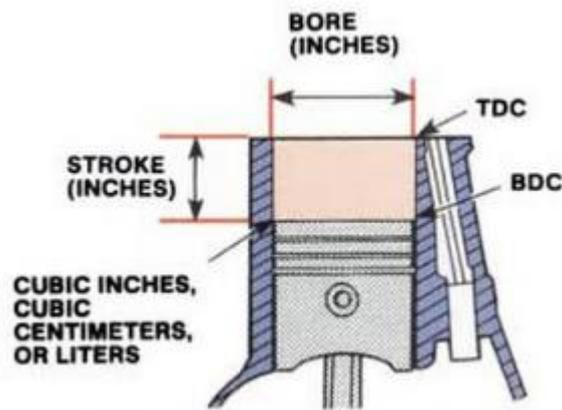


Figure 37: Section of a cylinder indicating the stroke, bore, TDC and BDC [ERKJA05]

In order to reduce the engine displacement there are four possibilities:

- Fixed reduction of piston displacement
- Reduced the number of cylinders to a fixed number

4.3. Methods of improving performance

This solution of reducing the engine displacement have generated a reduction of not only the fuel consumption and emissions but also of performance. To be competitive, these downsized engines must get improved to be compared with larger models with better performance. For this purpose, some technologies, or a combination of them, can be applied to the smaller engines:

- Forced induction (FI)
 - o Supercharging
 - o Turbocharging
 - o Wave-compression device
- Direct injection (DI)

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- Variable valve timing (VVT), variable valve lifting (VVL) and variable valve timing and lifting (VVTL)

4.3.1. Forced induction (FI)

Engines can be classified as naturally aspirated (NA) engines and engines with forced induction (FI). NA engines are the ones in which the air induction is solely produced by the pressure difference between the air intake system and the backward motion of the cylinder. The density of the inducted air depends on the design of the intake system and the higher density, the greater performance is obtained by the engine by increasing the mean effective pressure. On the other hand, in FI engines there is a torque and power enhancement by an increment of the air pressure entering the cylinder, what in entails is a higher density of it, which results in more oxygen in the cylinder and, as a consequence, a better performance is achieved, especially at high engine speeds where increment of horsepower can be up to 50%, although most of passenger cars do not reach these numbers [DORR04] [NUNN88].

The main compression effect that both engines share is the one produced by the piston during the compression stroke. This process starts with the cylinder filled with the air, in a diesel engine, or with the air-fuel mixture, in a gasoline engine, with the gas molecules being compressed in a smaller space while the piston is moving towards the TDC. Thus, there is an increment in the kinetic energy of the molecules that when the burning appears is released against the piston which is pushed downwards. In this process the relation between the whole cylinder's volume and the volume engaged between the TDC and the cylinder head, known as clearance volume, is called compression ratio. It is common that petrol engines have $CR = 7:1 - 10:1$ and diesel engines $CR = 14:1 - 24:1$ [CROL09].

$$CR = \frac{V_s + V_c}{V_c}$$

Where CR = compression ratio, V_s = Swept volume (cm^3) and V_c = clearance volume (cm^3).

The higher the CR , the more thermal efficiency, but there is a limit for the CR , and it is in the value which causes the effect known as knocking. Spark knock or knocking is an abnormal combustion produced by an alternative source instead, to the flame front of the spark plug, producing an irregular burning of the air-fuel mixture. This effect has different magnitudes, from a minimal detonation common in loading situations, to an intense effect that can have as a consequence a hole in a piston or melting a spark plug electrode. Low fuel octane or extreme temperature and pressures, caused by excessively lean mixtures or overly high CR in combination with high pressure compressors, are some of the causes of this phenomenon [GOOD19].

Combining the knowledge about the knocking effect, the compression ratio and the forced induction it is possible to deduce that high pressures produced by the FI require lower CR in order to avoid the knocking. A result of the pressure boost originated by the intake manifold or the FI system and a concrete CR established by the engine

characteristics, known as geometrical compression ratio, produces an effective compression ratio, which is the one resulting in the engine (See *Figure 38*): For example, for an engine with an initial CR 8:1, adding a turbocharger that results in a boost pressure of 0.6 bar, the real CR would be 11:1. This fact entails the requirement, especially of gasoline engines, of reducing the CR when using FI system in order to avoid the knocking.

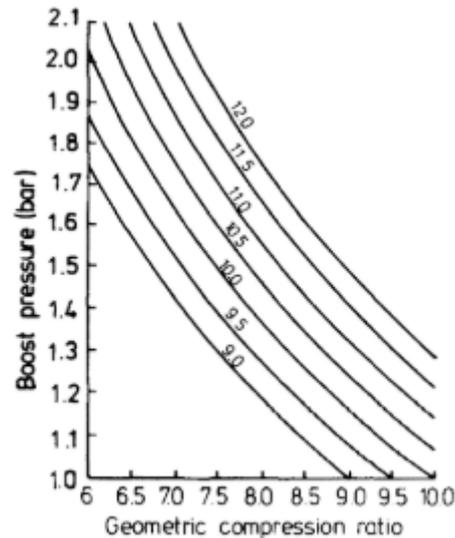


Figure 38: Relation between geometric compression ratio, boost pressure and effective compression ratio [JANO82]

FI can be applied to an engine in the following ways:

- Supercharging
- Turbocharging
- Pressure wave supercharger (PWS)

4.3.1.1. Supercharging

In this case part of the engine output power is used in a compressor which will increase the air pressure entering the combustion chamber, resulting in an improved filling of the cylinders and an improved scavenging of them, thus, there is an increase in the volumetric efficiency and a reduction in the fuel consumption and emissions. The main disadvantage is the subtraction of power from the engine and the limited. [ARIA08]

There are two main types of compressors:

- Rotary compressor: Its working principle is based on creating an increase of volume in the compressor inlet, which results in a pressure reduction in that zone, while at the outlet there is a reduction in the volume, emitting high pressurized air. They can be composed by lobes (Roots type) or by vanes (Vane type). [ALON09]
 - o Roots type: It is typically formed by two rotors, each with two or three lobes, both rotating in opposite directions and same speed. They do not compress the fluid, they only cause displacement, the compression of the fluid is produced when it is forced to leave the port. The greatest advantage is the inexistence of friction between the lobes, which

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makes unnecessary the lubrication of the mechanism, except for the rotor's bearings. [ALON09] [JAIN12]

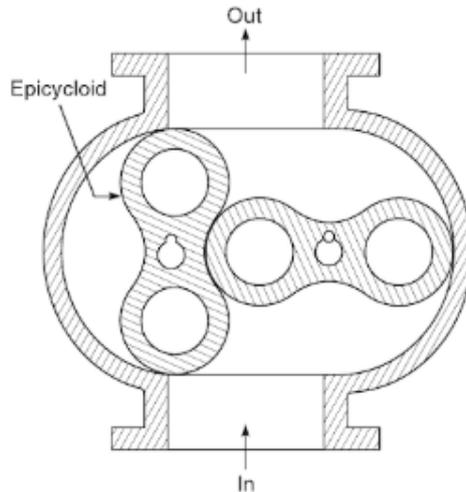


Figure 39: Roots type compressor [JAIN12]

- Vane type: It is formed by an eccentric drum coupled with multiple vanes. While the drum is rotating, the different vanes are being pushed outside by spring moving radially inside their own slot, continuously creating chambers of decreasing volume that result in a pressurized fluid. This would produce enormous amounts of friction between the vanes and the body interior wall; thus, a barrel joined to the rotor to provide a negligible clearance. [JAIN12]

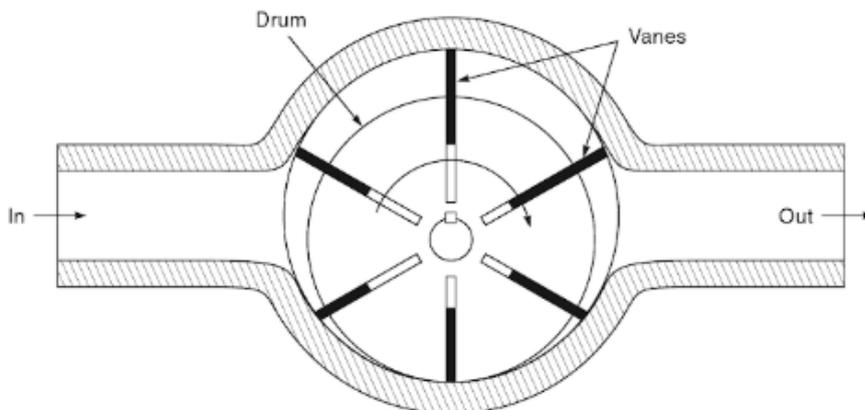


Figure 40: Vane type compressor [JAIN12]

- Centrifugal compressor: It is composed of numerous vanes attached to a rotor or impeller. It rotates at extremely high speeds between 10.000 and 15.000 rpm, when attached to the engine by a belt, and from 100.000 to 150.000 rpm, when being moved by a turbine, and it pushes the fluid to the exterior of the body by the centrifugal action, while it gains velocity over time. Then the fluid travels through the diffuser to reduce its speed and increase its pressure. [JAIN12]

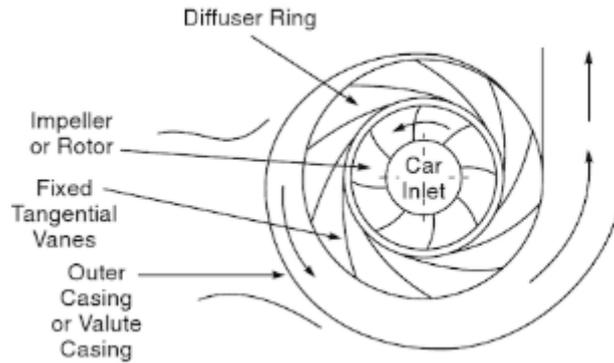


Figure 41: Centrifugal compressor [JAIN12]

4.3.1.2. Turbocharging

Turbocharging is based on the working principle of the supercharging, but instead of using the output energy of the engine to make the compressor work, with the respective power losses, it uses a turbine actuated by the exhaust gases of the engine.

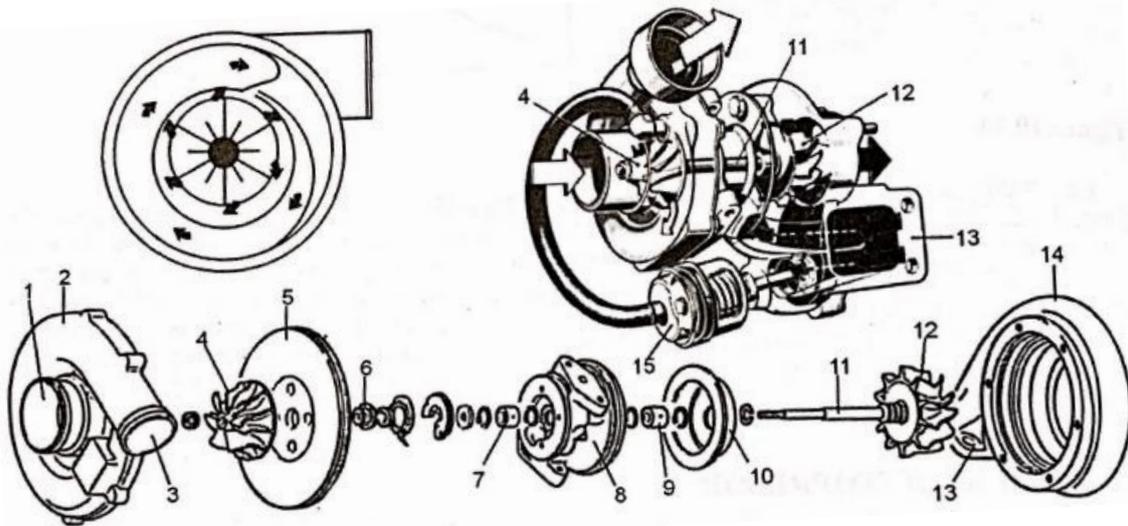


Figure 42: Scheme of a turbocharging [ALON09]

The system is composed by a compressor (4), typically a centrifugal one, attached by a shaft (11) to a turbine (12). Each part of the mechanism has its own independent case (2, 14). The engine exhaust gases are emitted through the exhaust manifold and they enter the turbine by the inlet canal (13). These high pressure, temperature and energetic gases are guided by the blades of the turbine axially to the center of it. This turbine must resist the highly demanding conditions of the exhaust gases and, thus, it must be made of materials such as chrome, nickel or even titanium. As the temperatures of the turbine can reach up to 1.050 °C [JANO82], the compressor is attached to a thermal wall (5) to prevent it to heat up, because the lower temperature of the intake gases, the higher oxygen content they have. The fresh fluids enter the compressor through the canal 1 and after the radial movement of the gases inside it and the effect of the diffuser, they exit the compressor through 3 guided to the intake manifold. Due to the extremely high achieved velocities, an improved lubricant mechanism must be used for the bearings and also with reducing

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thermal energy purpose. This is the reason why a large flow is needed for lubrication (approx. 10 l/min). [ALON09]

4.3.1.3. Pressure wave supercharger (PWS)

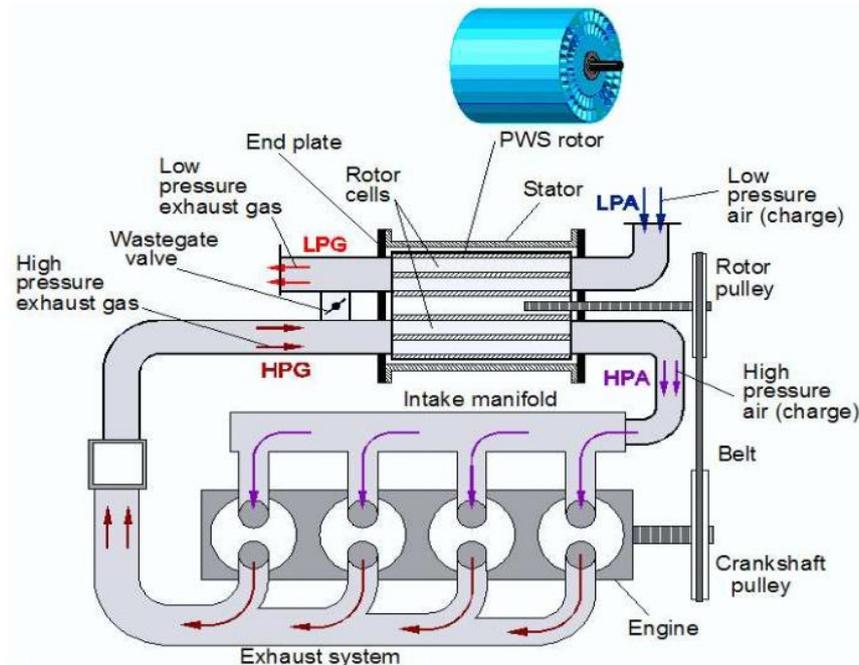


Figure 43: Pressure wave supercharger (PWS) working scheme [COST17]

The pressure wave supercharger (PWS), also known as wave compressor, is a device that uses the high pressure of the exhaust gases to transfer it to the incoming air by contact before reaching the combustion chamber, as shown in Figure 43. The working principle of this system is that if two fluids in contact in a long and narrow space have different pressures both equalize their pressures more rapidly than they mix with each other. When the high pressure exhaust gases (HPG) are leaving the cylinder they enter the PWS device, known as Compres (See Figure 44), which is rotating coupled to the engine's crankshaft by a belt and constituted by narrow, long and radial channels that are charged by one side with low pressure air (LPG) and in the other with HPG. After the interaction of the gases, both exit the PWS device being transformed: the LPG into high pressure air (HPA) and directed into the intake manifold and the HPG into low pressure exhaust gas (LPG) guided to the exhaust system [HEYW88] [COST17].

The main disadvantages of this method are the exchange of temperatures of both gases that leads to an undesirable increase of temperature in the intake air and a minimum mixture of both that will end in the combustion chamber. On the other hand, the effect is almost instantaneous unlike a turbocompressor which doesn't work on low rpm (Lag).

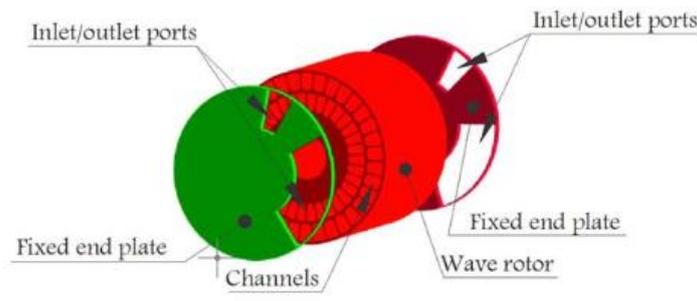


Figure 44: Scheme of a Compress [COST17]

4.3.2. Direct injection

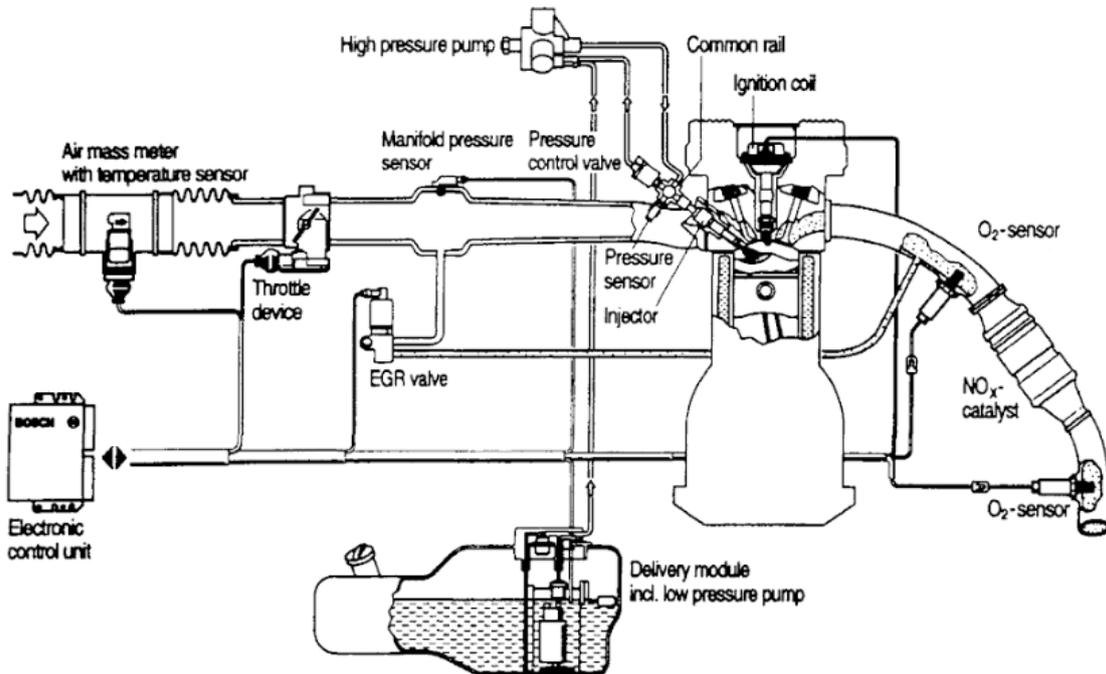


Figure 45: Gasoline direct injection scheme [ZHAO00]

Direct injection is a significant progress respect with the port injection because almost all the fuel used for the combustion is oxidized by the oxygen, resulting in a higher efficiency, and the possibility of injecting fuel multiple times during one cycle. The main disadvantage of this technology is the formation of nitrous oxides with leaner mixtures that force the addition of a three-way catalyst (TWC) and an exhaust gas recirculation (EGR) system. The injection of fuel is done with a pressure of up to 120 bar which, in combination to the proper design of the intake manifold, leads to a better atomization of the fuel and a more turbulent air in the combustion chamber, allowing the use of leaner mixtures. In addition, this vaporized fuel produces a short temperature reduction when injected in the combustion chamber with the high temperature air, resulting in an increase of the efficiency [ALON09].

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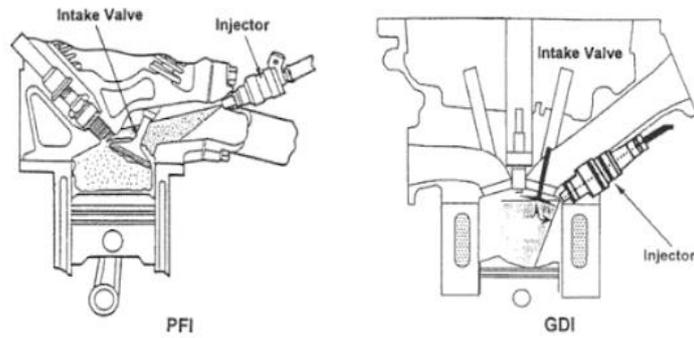


Figure 46: Comparison between port fuel injection (PFI, left) and gasoline direct injection (GDI, right) systems [ZHAO00]

4.3.2.1. Stratified-charge combustion

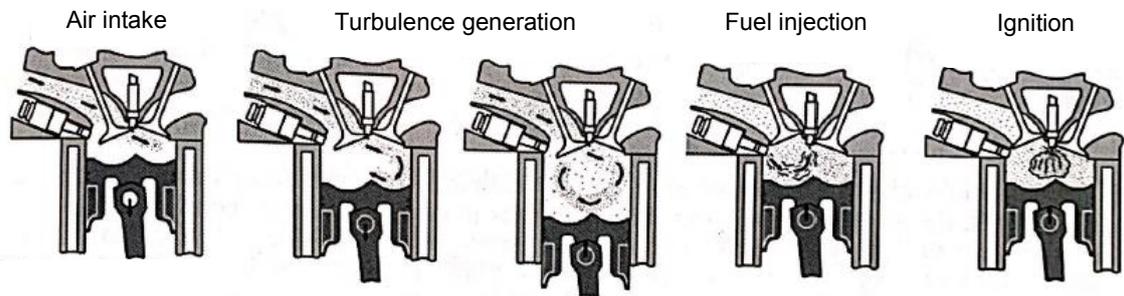


Figure 47: Scheme of stratified-charge direct injection process [ALON09]

It is an operation mode used when the engine speed is up to 3.500 rpm and the needed torque is low. The gasoline is injected right before the spark is produced, during the end of the compression stroke, which result in a non-uniform distribution along the combustion chamber, thus, this method allows the use of ultra-lean mixture (Up to 40:1). This fact derives in the reduction of fuel consumption, but the disadvantage is the formation of nitrogen oxides which makes necessary an EGR system. [ARIA08] [ALON09]

4.3.2.2. Homogeneous-charge combustion

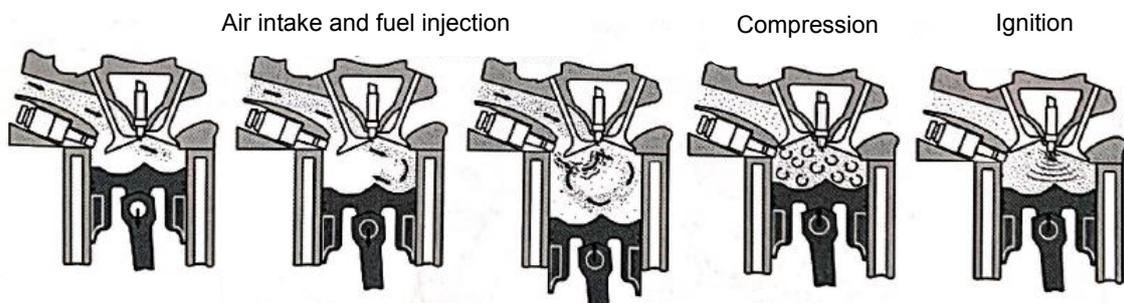


Figure 48: Scheme of homogeneous-charge direct injection process [ALON09]

When a higher torque and engine speed is needed there is a change in the injection from the stratified charge, introduced at the end of the compression, to the homogeneous

charge, which is originated at the beginning of the intake stroke. This leads to the correct distribution of the fuel in the combustion chamber and its combination with the production of an approximately perfect stoichiometric mixture (14,7:1) results in the optimal performance for achieving greater power. Furthermore, the stoichiometric mixture leads to lower pollutant emissions. [ARIA08] [ALON09]

4.3.2.3. Lean homogeneous-charge combustion

As the shift between the stratified-charge mode to the homogeneous-charge one is not instantaneous, there are various intermediate modes controlled by the electronic control unit (ECU) and one of this consists in the use of the homogeneous-charge mode with a lean mixture, resulting in less fuel consumption. [ARIA08] [ALON09]

4.3.2.4. Homogenous-charge and stratified-charge combustion

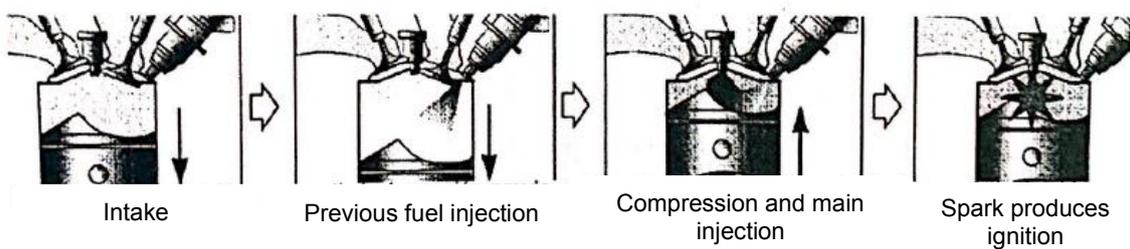


Figure 49: Scheme of homogeneous-charge and stratified-charge direct injection process [ALON09]

This method is another intermediate situation in the course from the stratified-charge method to the homogeneous-charge one. It consists in a previous injection of fuel during the intake, with the advantage of a proper distribution of the fuel, and a main one at the end of the compression, which objective is to ensure the start of the ignition even with considerable lean mixtures. This method has a lower fuel consumption. [ARIA08] [ALON09]

4.3.2.5. Homogeneous-charge and stratified-charge antiknock combustion

The working principle is the same as the previous one, but the difference is that the stratified charge avoids the detonation as previously mentioned, which leads to an optimal ignition angle, thus, higher torque is produced. [ARIA08] [ALON09]

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4.3.3. Variable valve timing (VVT), variable valve lifting (VVL) and variable valve timing and lifting (VVTL)

Table 9: Possible situations of variable valve timing and lifting [NRC_15]

Operating Condition	Intake Valve Timing	Exhaust Valve Timing	Valve Overlap
Wide-open throttle - low speed • Maximize torque	Early closing	Late opening	Decreased
Wide-open throttle - high speed • Maximize power	Late closing	Early opening	Increased
Light load • Reduced pumping losses • Maximize expansion work	Late closing (compression ratio lower than expansion ratio), or early closing (intake valve throttling)	Late opening	
Light load • Internal EGR gas retention for lean gas/fuel ratio		Late closing	Increased
Idle stability			Minimized

Variable valve lifting and timing is a technology used for solving the problem of adaptation of the engine cycle to its speed [NCR_15]:

- Low speed engine – wide-open throttle: The engine needs maximum torque, then the overlap should be lower in order to let just the needed air and start the compression before.
- High speed – wide-open throttle: With the objective to maximize the power of the engine, the overlap must be as high as possible to find the better scavenging and, thus, having more fresh air and less residual mixture in the cylinder.
- Light load: In order to minimize the emissions, the valves will need to retain some of the residual gases in the cylinder working as an internal EGR system.
- Idle: The main aim is the great stability of the engine thus the overlap should be minimized.

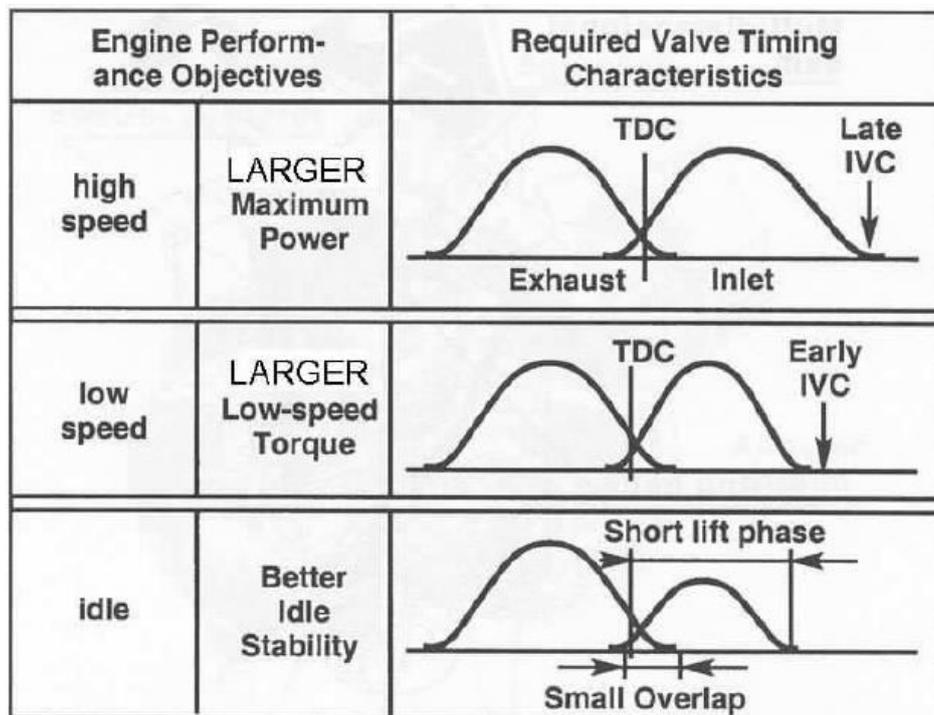


Figure 50: Diagram of variable valve timing and lifting effect in different engine situations [CHEH96]

4.4. Rightsizing

4.4.1. Introduction

Downsizing has been one of the main objectives of development in IC engines over the last decade. However, in order to fulfill costumers' needs of operation as transporting heavier cargo, but without compromising the fuel consumption and emissions, a new engine trend has emerged known as rightsizing, where the engine displacement is no longer being reduced but the appropriate size has been searched [SROK19].

The combustion process has certain parameters defining the way and the quantity of energy that will be obtained from the fuel. Thus, changing the volume of the combustion chamber will affect this process. In this new trend of rightsizing, variations in the swept volume can be translated into an increase or reduction of the displacement volume [SROK19].

In the development of both rightsizing and downsizing, common technologies are used in order to maintain or improve the performance of the unit power: Forced induction, direct fuel injection and variable valve timing [SROK19]

- Forced induction: It is the simplest method to equalize a reduction of the displacement volume of an engine, minimizing power losses and allowing the burn of leaner mixtures. Adding a single turbocharger or a twin-turbo and frequently using an intercooler, driving a compressor with permanent or variable parameters of the turbine is the most common process of improving the filling of the cylinder.
- Direct fuel injection: It is a technology that supports the proper atomization of fuel droplets and the injection of fuel multiple times in the same stroke in the optimal situations, resulting in a complete evaporation and combustion. It has improvements in both downsizing, due to the restoring of the power losses, and in rightsizing, where it ensures the ability to work with leaner mixtures.
- Variable valve timing: It is a system that maintains or even enhances the filling of the combustion chamber, and thus the efficiency, by adjusting the valve timing to every engine situation, i.e., in various engine speeds and loads.

The combination of the three of them allows the stoichiometric combustion in downsized and rightsized engines.

4.4.2. The downsizing/rightsizing index (W_d)

Commonly, some experts define a degree of residue or change when downsizing an engine, but in [SROK19] a downsizing/rightsizing index (W_d) is defined as the intensity of the variations of the variables that constitute the cylindrical form of the combustion chamber, i.e., the diameter or bore of the cylinder and the stroke of the piston.

$$W_d = 1 - AB^2$$

$$A = \frac{S_d}{S} \quad B = \frac{D_d}{D}$$

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Where W_d = Downsizing index, A = Coefficient of change of piston stroke, S = Stroke of the piston – input state, S_d = Stroke of the piston in the downsized engine, B = Coefficient of change of cylinder’s diameter, D = Cylinder diameter – input state, D_d = Cylinder diameter in the downsized engine.

In real cases, even it is possible to modify only one of the two parameters (Piston stroke and cylinder diameter), frequently both are changed simultaneously thanks to its manufacturing possibility. These multiple combinations between the stroke and the diameter result in various downsizing/rightsizing indexes (W_d) that can coincide with different A and B coefficients. This mixture of parameters and its relationship with its corresponding indexes are shown in the *Figure 51* [SROK19].

												A										
												1.60	-0.60	-0.44	-0.30	-0.16	-0.02	0.10	0.22	0.32	0.42	
												1.55	-0.55	-0.40	-0.26	-0.12	0.01	0.13	0.24	0.35	0.44	
												1.47	-0.47	-0.33	-0.19	-0.06	0.06	0.17	0.28	0.38	0.47	
												1.45	-0.45	-0.31	-0.17	-0.05	0.07	0.18	0.29	0.39	0.48	
												1.39	-0.39	-0.25	-0.13	0.00	0.11	0.22	0.32	0.41	0.50	
												1.35	-0.35	-0.22	-0.09	0.02	0.14	0.24	0.34	0.43	0.51	
												1.28	-0.28	-0.16	-0.04	0.08	0.18	0.28	0.37	0.46	0.54	
												1.25	-0.25	-0.13	-0.01	0.10	0.20	0.30	0.39	0.47	0.55	
												1.22	-0.22	-0.10	0.01	0.12	0.22	0.31	0.40	0.48	0.56	
												1.15	-0.15	-0.04	0.07	0.17	0.26	0.35	0.44	0.51	0.59	
												1.08	-0.08	0.03	0.13	0.22	0.31	0.39	0.47	0.54	0.61	
												1.05	-0.05	0.05	0.15	0.24	0.33	0.41	0.49	0.56	0.62	
B	1.60	1.55	1.50	1.45	1.40	1.35	1.30	1.25	1.20	1.15	1.10	1.05	W_d	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60
	-1.56	-1.40	-1.25	-1.10	-0.96	-0.82	-0.69	-0.56	-0.44	-0.32	-0.21	-0.10	1.00	0.00	0.10	0.19	0.28	0.36	0.44	0.51	0.58	0.64
	-1.46	-1.31	-1.16	-1.02	-0.88	-0.75	-0.62	-0.50	-0.38	-0.27	-0.16	-0.06	0.96	0.04	0.13	0.22	0.31	0.39	0.46	0.53	0.59	0.65
	-1.30	-1.16	-1.03	-0.89	-0.76	-0.64	-0.52	-0.41	-0.30	-0.19	-0.09	0.01	0.90	0.10	0.19	0.27	0.35	0.42	0.49	0.56	0.62	0.68
	-1.20	-1.07	-0.94	-0.81	-0.69	-0.57	-0.45	-0.34	-0.24	-0.14	-0.04	0.05	0.86	0.14	0.22	0.30	0.38	0.45	0.52	0.58	0.64	0.69
	-1.05	-0.92	-0.80	-0.68	-0.57	-0.46	-0.35	-0.25	-0.15	-0.06	0.03	0.12	0.80	0.20	0.28	0.35	0.42	0.49	0.55	0.61	0.66	0.71
	-1.00	-0.87	-0.76	-0.64	-0.53	-0.42	-0.32	-0.22	-0.12	-0.03	0.06	0.14	0.78	0.22	0.30	0.37	0.44	0.50	0.56	0.62	0.67	0.72
	-0.82	-0.71	-0.60	-0.49	-0.39	-0.29	-0.20	-0.11	-0.02	0.06	0.14	0.22	0.71	0.29	0.36	0.42	0.49	0.55	0.60	0.65	0.70	0.74
	-0.65	-0.55	-0.45	-0.36	-0.26	-0.18	-0.09	-0.01	0.07	0.15	0.22	0.29	0.65	0.36	0.42	0.48	0.53	0.59	0.64	0.68	0.73	0.77
	-0.51	-0.42	-0.33	-0.24	-0.16	-0.08	0.00	0.08	0.15	0.22	0.29	0.35	0.59	0.41	0.47	0.52	0.57	0.62	0.67	0.71	0.75	0.79
	-0.38	-0.30	-0.22	-0.14	-0.06	0.02	0.09	0.16	0.22	0.29	0.35	0.40	0.54	0.46	0.51	0.56	0.61	0.65	0.70	0.74	0.77	0.81
	-0.28	-0.20	-0.13	-0.05	0.02	0.09	0.16	0.22	0.28	0.34	0.40	0.45	0.50	0.50	0.55	0.60	0.64	0.68	0.72	0.76	0.79	0.82
	-0.13	-0.06	0.01	0.07	0.14	0.20	0.26	0.31	0.37	0.42	0.47	0.51	0.44	0.56	0.60	0.64	0.68	0.72	0.75	0.78	0.81	0.84
	-0.02	0.04	0.10	0.16	0.22	0.27	0.32	0.38	0.42	0.47	0.52	0.56	0.40	0.60	0.64	0.68	0.71	0.74	0.78	0.80	0.83	0.86
	0.09	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.49	0.53	0.57	0.61	0.36	0.65	0.68	0.71	0.74	0.77	0.80	0.83	0.85	0.87
	0.23	0.28	0.33	0.37	0.41	0.45	0.49	0.53	0.57	0.60	0.64	0.67	0.30	0.70	0.73	0.76	0.78	0.81	0.83	0.85	0.87	0.89

Figure 51: Matrix of the downsizing/rightsizing index (W_d) with selected cells marked with the same values of index $W_d=0,22$ [SROK19]

In this matrix, the yellow cells represent values of coefficients A and B and the rest are W_d values. These W_d indexes resulting of the multiple possibilities of combining A and B defining the geometry of the combustion chamber. If W_d is positive, it represents the decreased volume of the engine (Downsizing), while negative values mean an increased displacement (Upsizing). From *Figure 51*, what has been already established about one concrete downsizing/rightsizing index having more than one possible combination of the A and B coefficients is proved as $W_d = 0.22$, which can be a real example of a 1.8 dm³ engine reduced into a 1.4 dm³ (1.8 x (1 - 0.22) = 1.4), with coefficients $A = 0.50-1.60$ and $B = 0.70-1.25$.

Table 10: Possible values of A and B coefficients being $W_d=0.22$ in all cases [SROK19]

No	Coefficient A		Coefficient B		B/A	Remarks
	value	form	value	form		
1.	1.60	upsizing	0.70	downsizing	0.44	Analyze range
2.	1.39		0.75			
3.	1.22		0.80			
4.	1.08		0.85			
5.	0.96	downsizing	0.90	neutral	0.94	
6.	0.86		0.95	upsizing	1.10	
7.	0.78		1.00		1.28	
8.	0.71		1.05		1.48	
9.	0.65		1.10		1.69	
10.	0.59		1.15	1.95		
11.	0.54		1.20	2.22		
12.	0.50		1.25	2.50		

With this established range of values for the piston stroke and cylinder diameter in combination with the information obtained from the Engine of the Year Competition, the possible values for the ratio between the cylinder diameter and the piston stroke are from 0.79 to 1.28. Therefore, considering the relationship of the coefficients A and B and the cylinder diameter and piston stroke, the resulting range of values for the coefficients of $W_d = 0.22$ (Table 10): A = 0.78-1.08 and B = 0.85-1.00 [SROK19].

4.4.3. The efficiency of a generalized engine in relation to rightsizing

The air-fuel mixture is the working medium of an engine and it is what supports the thermodynamic variations, including the changes in volume. These thermodynamic changes are represented by the efficiency (η_t) graphically in the Figure 52 and mathematically [SROK19]:

$$\eta_t = 1 - \frac{\frac{\lambda_p \rho_p \varepsilon_s^{k-1}}{\delta^{k-1}} + \kappa(\rho' - 1) - \rho'}{\varepsilon_s^{k-1} \{ \lambda_p [\kappa \rho_p - (\kappa - 1)(1 + \rho_p \ln \rho_T)] - 1 \}}$$

Downsizing

Where η_t = Theoretical efficiency of the work cycle, λ_p = Degree of pressure increase during isochoric heat transfer, ρ_p = Degree of expansion during isobaric heat transfer, ε_s = Effective compression ratio, κ = Isentropic exponent, δ = Degree of another expansion process, ρ' = Degree of pre-compression when heat is drained at constant pressure, ρ_T = Degree of expansion during isothermal heat transfer.

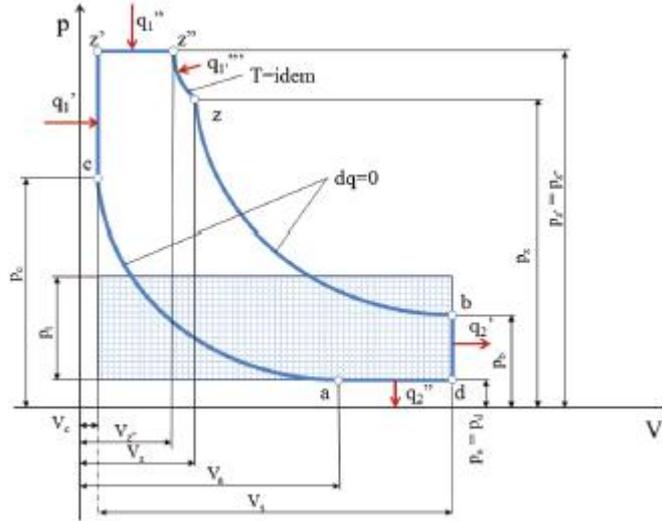


Figure 52: Generalized Otto-Sabathe cycle of a four-stroke IC engine [SROK19]

When combining the formula of efficiency and the volume change function, the efficiency can be described by the variations in the engine swept volume [SROK19].

$$\eta_t = 1 - \frac{\lambda_p \left(\frac{V_{z'}}{V_c}\right) \left(\frac{V_a}{V_c}\right)^{\kappa-1}}{\left(\frac{V_b}{V_z}\right)^{\kappa-1} + \kappa \left[\left(\frac{V_b}{V_a}\right) - 1\right] - \frac{V_b}{V_a}} \left\{ \lambda_p \left[\kappa \left(\frac{V_{z'}}{V_c}\right) - (\kappa-1) \left(1 + \left(\frac{V_{z'}}{V_c}\right) \ln\left(\frac{V_z}{V_{z'}}\right)\right) \right] - 1 \right\}$$

The parameters λ_p , V_a , V_z , $V_{z''}$, κ are related to the fuel properties and V_b and V_c are resulting from the constitution of the combustion space and thus related to the idea of rightsizing. There are three possible situations in the development of the rightsizing idea [SROK19]:

- $V_{sd} \neq V_s$; $V_{cd} = V_c$; $\varepsilon_d \neq \varepsilon$

In this case, the swept volume of the engine, V_s , is changed to V_{sd} and the volume related to the compression is maintained, thus the compression ratio, ε , is different.

- $V_{sd} \neq V_s$; $V_{cd} \neq V_c$; $\varepsilon_d \neq \varepsilon$

In this situation both the swept volume, V_s , and the volume of the compression space, V_c , are changed. This could be as a rightsizing case when either the volume related to the compression (V_{cd}) or the geometric compression ratio (ε_d) is known and treated as an input.

- $V_{sd} \neq V_s$; $V_{cd} \neq V_c$; $\varepsilon_d = \varepsilon$

This case occurs when both swept and compression volumes are changed in such a way that they maintain the compression ratio, as in the case of the *Table 10*, where the downsizing/rightsizing index is maintained with a variety of combinations of the stroke and the diameter, corresponding to the swept and compression volumes.

Generally, the known input variable is the compression ratio as it is what defines the proper self-ignition in diesel engines and the limit of knocking for gasoline engines. The last efficiency formula in combination with these considerations about rightsizing results in [SROK19]:

$$\eta_t = 1 - \frac{\frac{\lambda_{pd} \left(\frac{V_{z'd}}{V_{cAB^2}}\right) \left(\frac{V_{ad}}{V_{cAB^2}}\right)^{\kappa_d - 1}}{\left(\frac{V_b}{V_z}\right)^{\kappa - 1}} + \kappa_d \left[\left(\frac{(V_s + V_c)AB^2}{V_{ad}}\right) - 1 \right] - \frac{(V_s + V_c)AB^2}{V_{ad}}}{\left(\frac{V_{ad}}{V_{cAB^2}}\right)^{\kappa_d - 1} \left\{ \lambda_{pd} \left[\kappa_d \left(\frac{V_{z'd}}{V_{cAB^2}}\right) - (\kappa_d - 1) \left(1 + \left(\frac{V_{z'd}}{V_{cAB^2}}\right) \ln \left(\frac{V_{z'd}}{V_{z'd}}\right) \right) \right] - 1 \right\}}$$

4.4.4. Real case study

In [SROK19], there is a study of the Volkswagen 1.4 TSI engine which is the downsized version of the 1.8 FSI one. The downsizing/rightsizing index in this case is $W_d = 0.22$ which coincides with the *Table 10*, the data from this table is appropriate for this case.

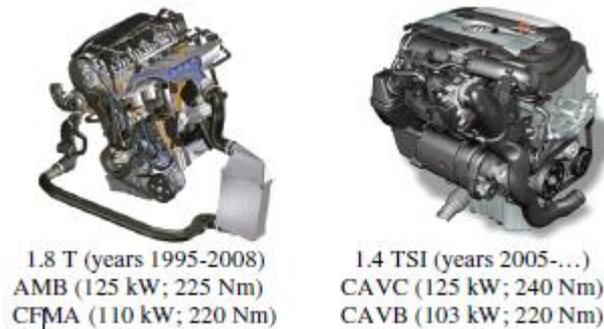


Figure 53: Volkswagen 1.8 FSI engine (Left) and Volkswagen 1.4 TSI engine (Right) [SROK19]

Downsizing

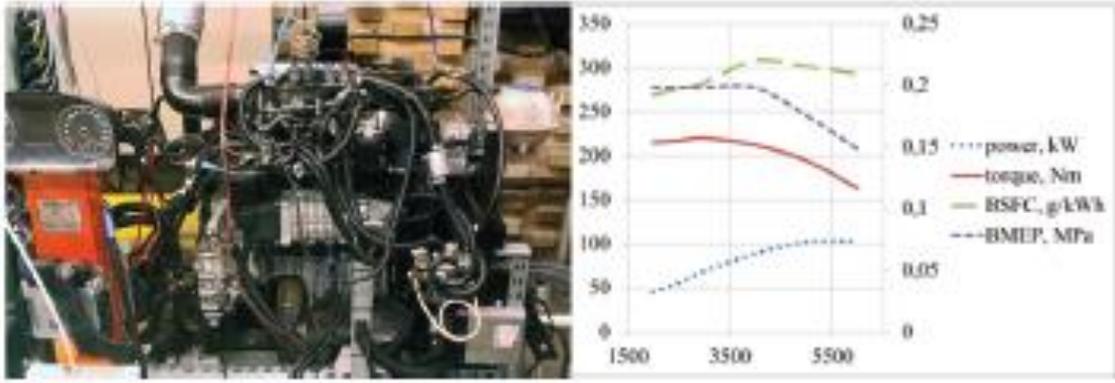


Figure 54: Volkswagen 1.4 TSI engine on the test bench and its performance map [SROK19]

Above of all the values of the *Table 10*, four of the points were adopted for the research and introduced in the efficiency equation resulting in the *Table 11*, all maintaining the geometrical compression ratio ($\epsilon_d = \epsilon$) [SROK19].

Table 11: Theoretical efficiency values for a generalized engine cycle with $W_d = 0.22$ for various values of the coefficients A and B [SROK19]

A	B	W_d	η_e
1.08	0.85	0,220	0,502
0.96	0.90	0,222	0,500
0.86	0.95	0,224	0,499
0.78	1.00	0,220	0,502

From *Figure 55*, it can be established that the values of the coefficients A and B have a minimum impact in the theoretical efficiency of the engine cycle. The central line is the average efficiency and the dash line the possible deviations [SROK19].

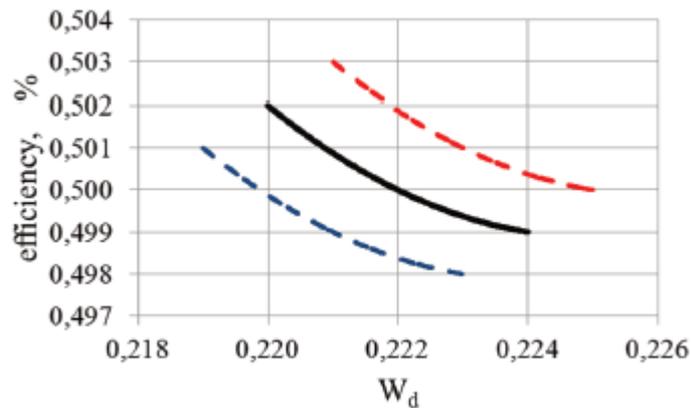


Figure 55: Relation between efficiency and downsizing/rightsizing index (W_d) [SROK19]

5. DOWNSIZED AND RIGHTSIZED IC ENGINES AND GREENHOUSE EFFECT

5.1. Greenhouse gases emissions in Europe

Greenhouse gases are one of the most important concerns nowadays and, thus, how they have progressed, and which sources are the greatest responsible, must be evaluated.

5.1.1. Total greenhouse gases emissions

In general terms, greenhouse gas emissions have been decreasing over the last three decades (See *Figure 56*). Since 1990, where the amount of net emissions, in CO₂ equivalent numbers, reached over 5.500 million tonnes, which compared to the quantity of 2017, around 4.400 million tonnes, is a reduction of approx. 20%, especially in the two first decades of the analysis. Even this is a great development it has not been enough due to the continuous rising global temperature (See *Figure 29*). Furthermore, it is represented also the influence of Land Use, Land-Use Change and Forestry (LULUCF), which considers the natural sinks of the soils and plants, and they have an important contribution to a reduction of approx. 5%, which largest influence comes based on the reduction of CO₂ with the photosynthesis effect of plants and the absorption properties of soil.

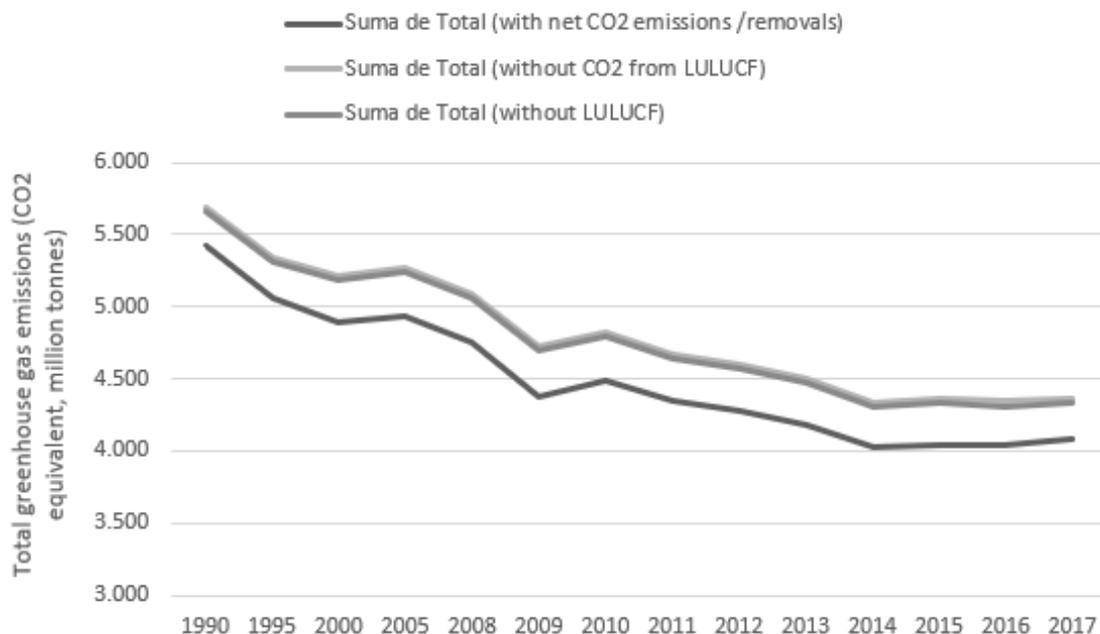


Figure 56: Evolution of emissions of greenhouse gases (CO₂ equivalent) in Europe from 1990 to 2017 [EEA_19AEUGHG119]

In addition to this evaluation of the emission progress, the sources of the same must be taken into account in order to define which has been the sectors with higher declines and which should be improved. According to *Figure 57*, all four main sectors have maintained a nearly constant share in the overall contribution, with minimal diminutions in the energy sector. Another fact that can be observed is that the energy,

Downsized and rightsized IC engines and greenhouse effect

agriculture, industrial processes and product use are the main sectors with a negligible contribution of other external sectors.

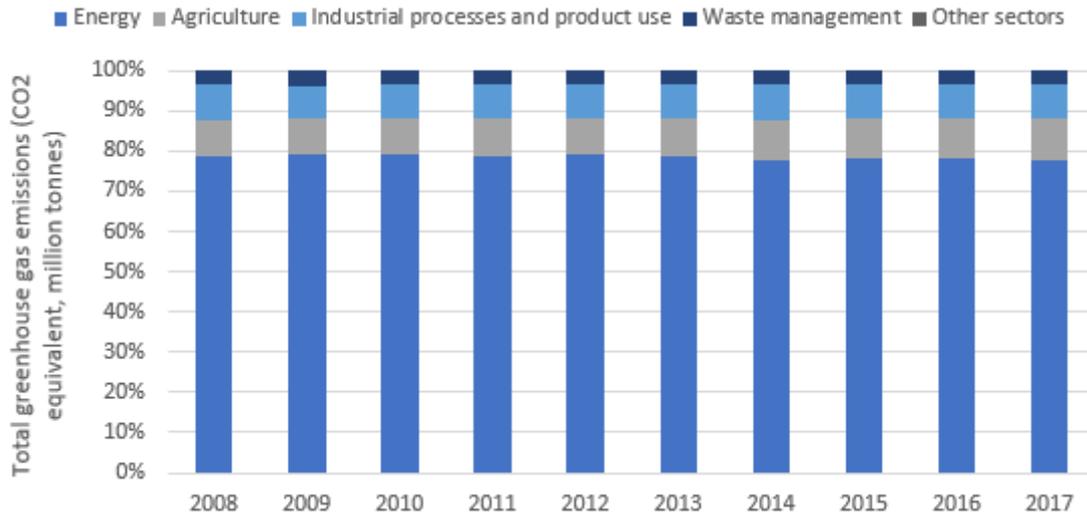


Figure 57: Total greenhouse gases emissions' proportional share by source in Europe from 1990 to 2017 [EURO19GHGESS]

5.1.2. Carbon dioxide (CO₂) emissions

As previously commented, the carbon dioxide is the most important gas, not because of its high abilities of radiation absorption, but due to the extremely amounts of emissions of the same. Its progression can be observed in *Figure 58*, where it is shown a reduction of approx. 17% from the data of 1990. This means that the carbon dioxide is not only the biggest contributor in the greenhouse effect, but it has been notoriously reduced in the last decades. As mentioned in the analysis of the total greenhouse gases emissions, the natural sinks of LULUCF have an important contribution to the reduction of this gas estimated in approx. 8% in 2017.

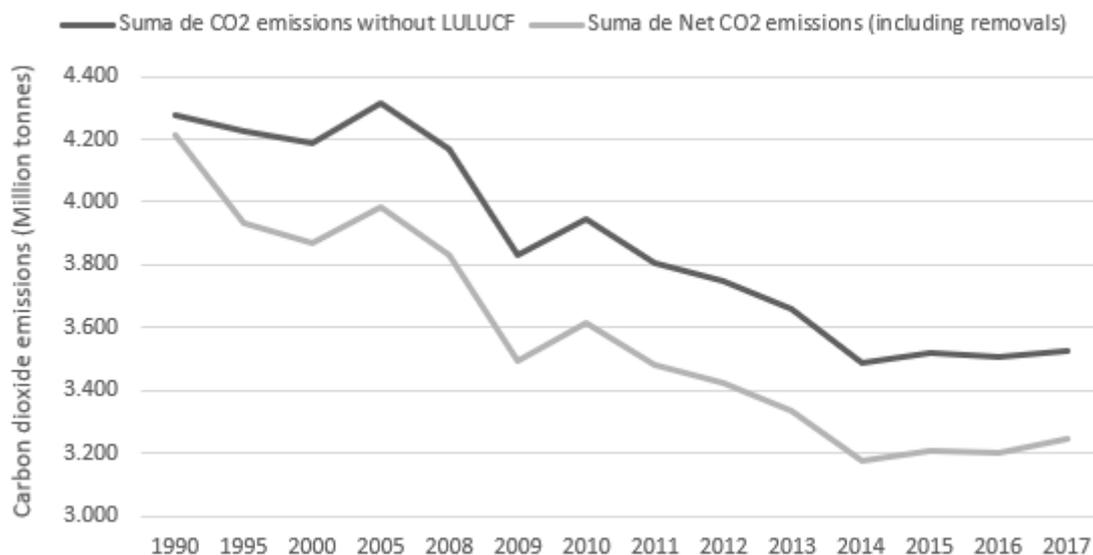


Figure 58: Evolution of carbon dioxide emissions in Europe from 1990 to 2017 [EEA_19AEUGHGI19]

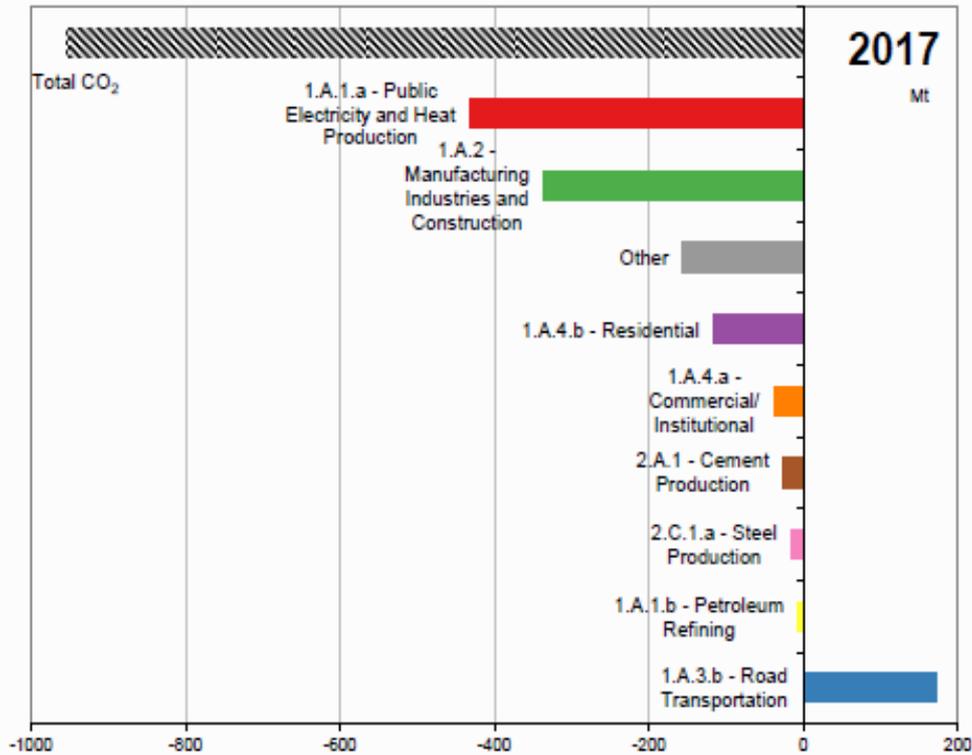


Figure 59: Change in carbon dioxide emissions by main sources in Europe in 2017 relative to 1990 [EEA_19AEUGHG119]

Evaluating in depth the sources of carbon dioxide in *Figure 59*, the largest contributor to its reduction has been the production of electricity and heat in around 450 million tonnes from 1990 to 2017, whose change is due to the progressive implementation of alternative source of energy other than fossil fuels, and, from *Figure 60*, it is observable that currently it is the greatest responsible for its emission with a overall share of approx. 30%. Another remarkable evolution is the one from the sector of manufacturing and construction which embraces 14% of the total share and it has contributed with around 350 million tonnes of emissions diminution. On the other hand, road transportation has been the exclusive sector to increase its emissions' contribution with almost 200 million tonnes, being the second largest contributor of carbon dioxide emissions at this moment with 25% of the share.

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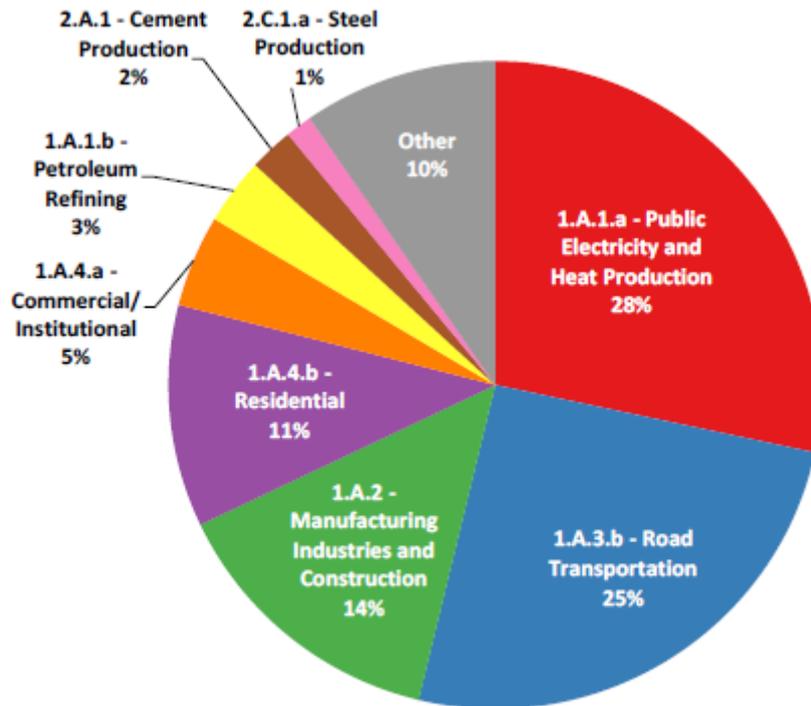


Figure 60: Carbon dioxide emissions' share by source in Europe in 2017 [EEA_19AEUGHG119]

5.1.3. Methane (CH₄) emissions

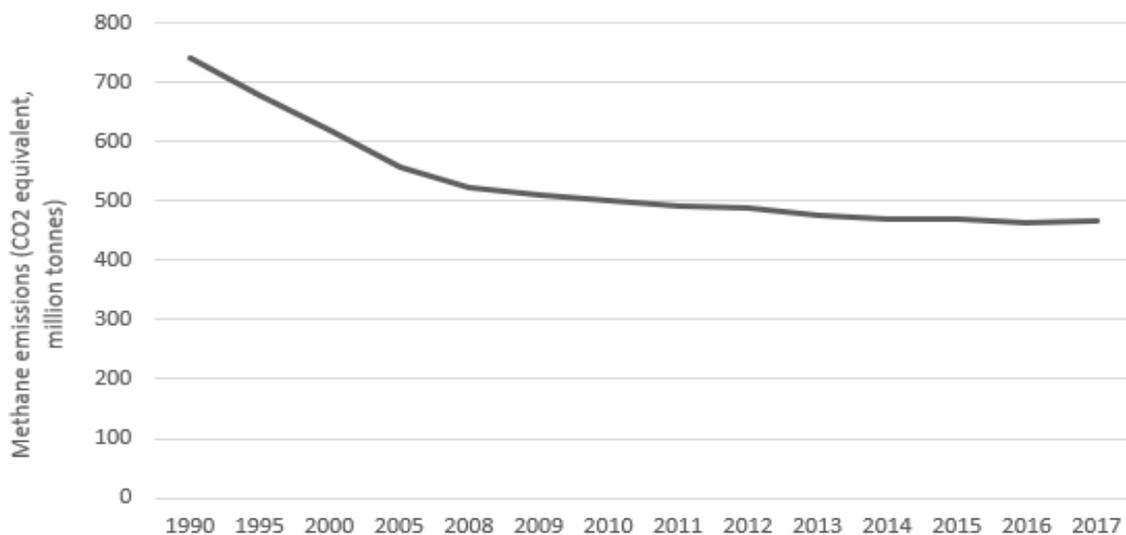


Figure 61: Evolution of methane emissions (CO₂ equivalent) in Europe from 1990 to 2017 [EEA_19AEUGHG119]

Methane is the second most significant contributor to the greenhouse effect with approx. 11% of the total mass of greenhouse gas emissions. Its quantity of emissions, transformed into its CO₂ equivalent value to let both gases be compared, have been decreasing over time especially till 2008 where there was a decrease of approx. 35%.

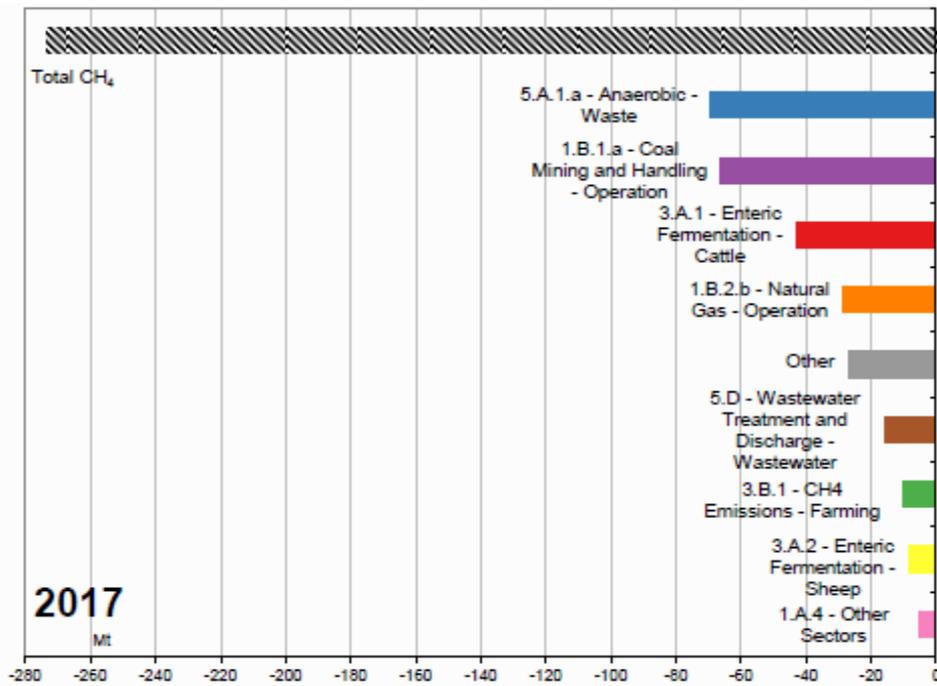


Figure 62: Change in methane emissions by main sources in Europe in 2017 relative to 1990 [EEA_19AEUGHGI19]

The leading sector in reducing the emissions of methane is the anaerobic waste treatment, which is an alternative to the traditional aerobic process advantageous due to its ability to recover the emissions of methane with the purpose of being used as an energy source [SATT11]. This anaerobic waste treatment together with activities related to coal mining and handling have achieved to reduce up to 140 million tonnes, that represents half of the total decrease in methane emissions. In addition, these two sectors embrace around 25% of the total share of emissions. Although, this important reduction the most powerful contributor to the emissions is the enteric fermentation sector, which consists in the share of methane produced by livestock as a result of the digestive process and it holds the 36% of all methane emissions, even after a reduction of over 50 million tonnes in the last three decades.

Downsized and rightsized IC engines and greenhouse effect

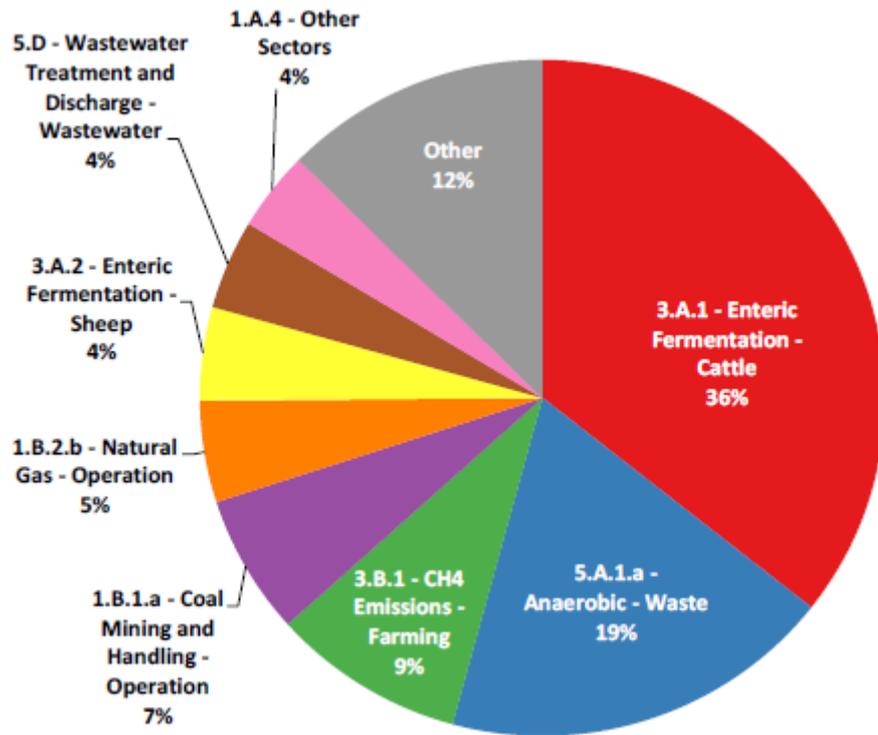


Figure 63: Methane emissions' share by source in Europe in 2017 [EEA_19AEUGHG119]

5.1.4. Nitrous oxide (N₂O) emissions

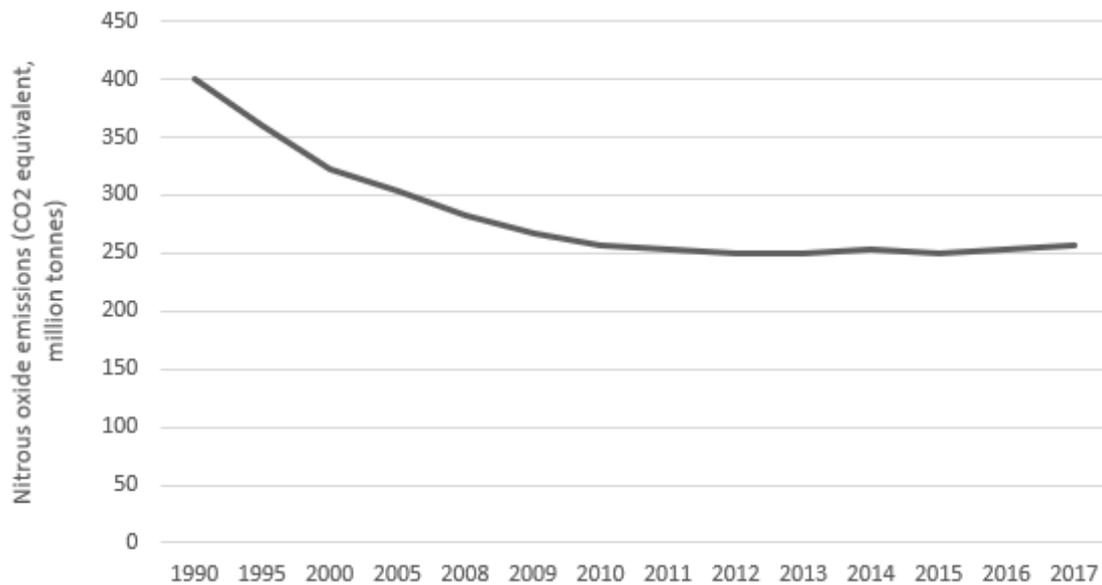


Figure 64: Evolution of nitrous oxide emissions (CO₂ equivalent) in Europe from 1990 to 2017 [EEA_19AEUGHG119]

Nitrous oxides are the third of the greenhouse gases with higher amounts of emissions being responsible of around 6% of the total emissions. Its evolution has been

abruptly especially the first two decades from the beginning of the analysis, with a diminution of almost 40% and it has maintained mostly constant over the last decade.

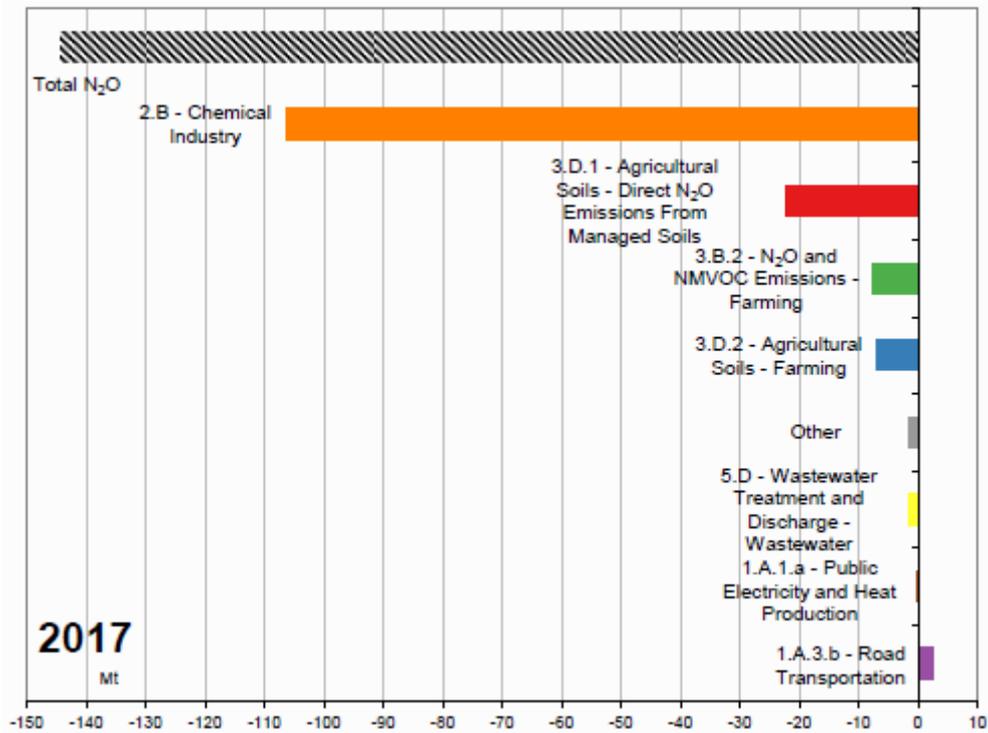


Figure 65: Change in nitrous oxide emissions by main sources in Europe in 2017 relative to 1990 [EEA_19AEUGHG119]

This mentioned decreased is shown by source sector in *Figure 65*, where it is represented that around 70% of the total reduction is owing to an enormous decline in the emissions of the chemical industry sector. This sector, among other production areas, includes the fabrication of plastic products, which is currently known as one of the most important and developing sectors (75% of increase from 2006 to 2016) [PLEU18]. As with the emissions of carbon dioxide, the unique sector that has increased its emissions from 1990 till 2017 is road transportation, even this growth has not been of such intense grade (Less than 5 million tonnes). In relation to its main sources, the agricultural sector union of nitrogen oxides, coming from soils and farming, accumulates over 70% of the whole amount of emissions. Even its influence is less effective, road transportation means 5% of the total emissions of nitrous oxides.

Downsized and rightsized IC engines and greenhouse effect

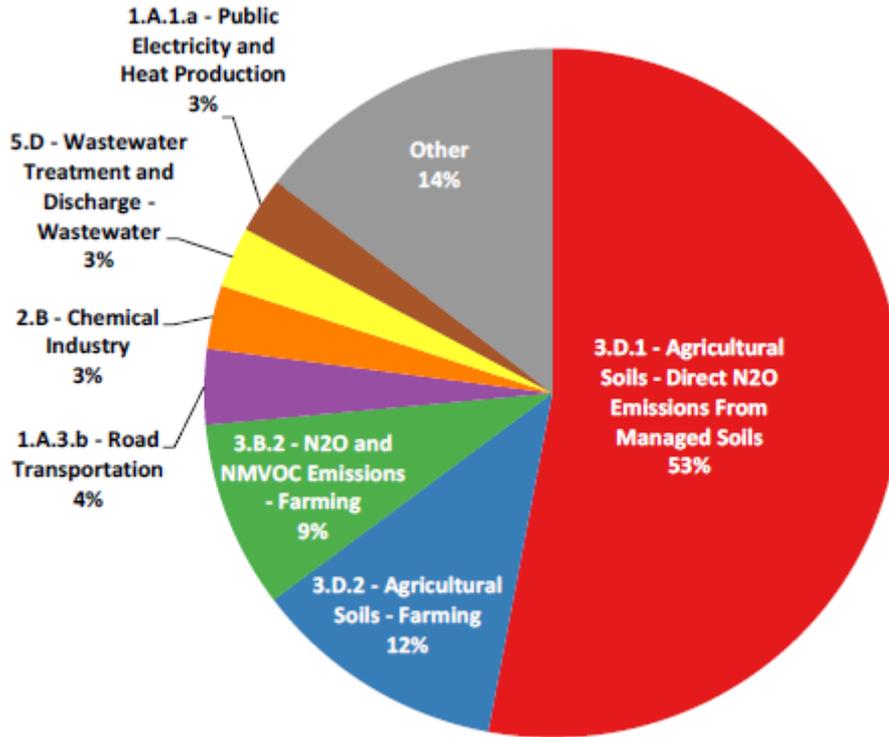


Figure 66: Nitrous oxide emissions' share by source in Europe in 2017 [EEA_19AEUGHG119]

5.1.5. Fluorinated gases emissions

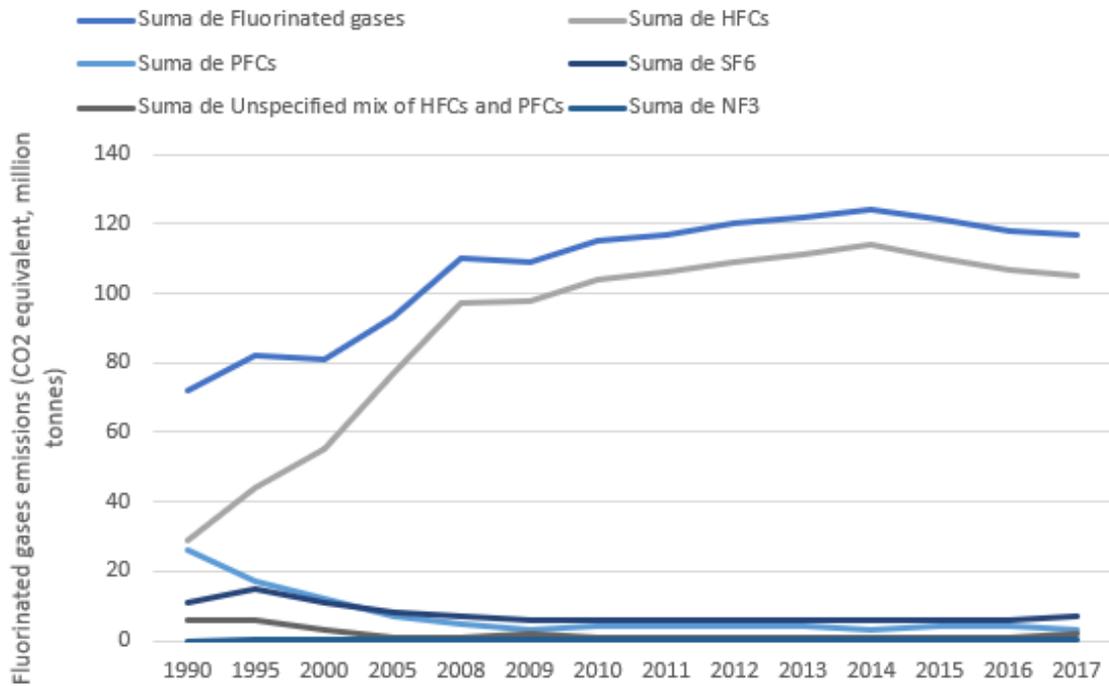


Figure 67: Evolution of fluorinated gases emissions (CO2 equivalent) in Europe from 1990 to 2017 [EEA_19AEUGHG119]

The fraction of all fluorinated gas emissions affords roughly 3% of the mentioned total emissions, but their lifetime and their radiative forcing are the highest of all greenhouse gases. This is the unique of all the previously mentioned gases that has keep growing since the beginning of the statistics back in 1990, reaching up to 125 million tonnes in 2014 (Roughly 40% more emissions than in 1990). It must be considered that among the 5 different types of fluorinated gases shown in *Figure 67*, hydrofluorocarbons (HFC) is the most representative them embracing up to 90% of all of them. This is the responsible for the growth of the fluorinated gases as the others have decreasing or maintaining over the last three decades.

This general increase in the fluorinated gases can be reflected in the *Figure 68*, in which it is shown the enormous growth from the refrigeration and air conditioning sector, where hydrofluorocarbons are used. This gas accounts over 80% of the emissions in 2017 after the increase from 1990 of approx. 95 million tonnes.

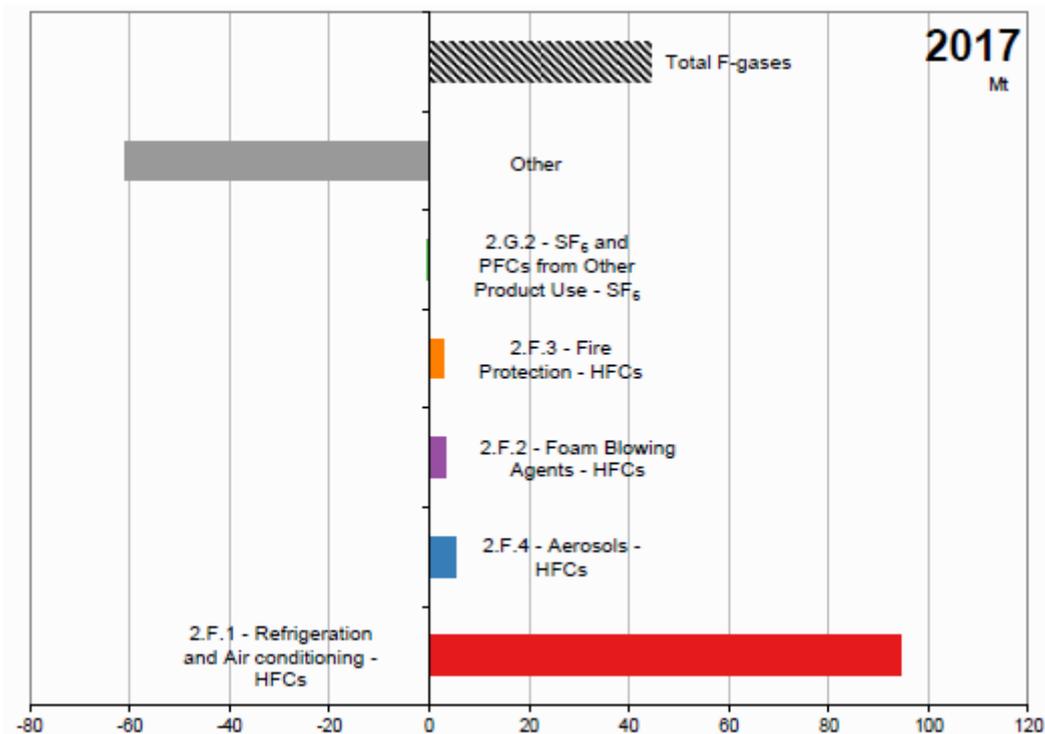


Figure 68: Change in fluorinated gases emissions by main sources in Europe in 2017 relative to 1990 [EEA_19AEUGHG119]

Downsized and rightsized IC engines and greenhouse effect

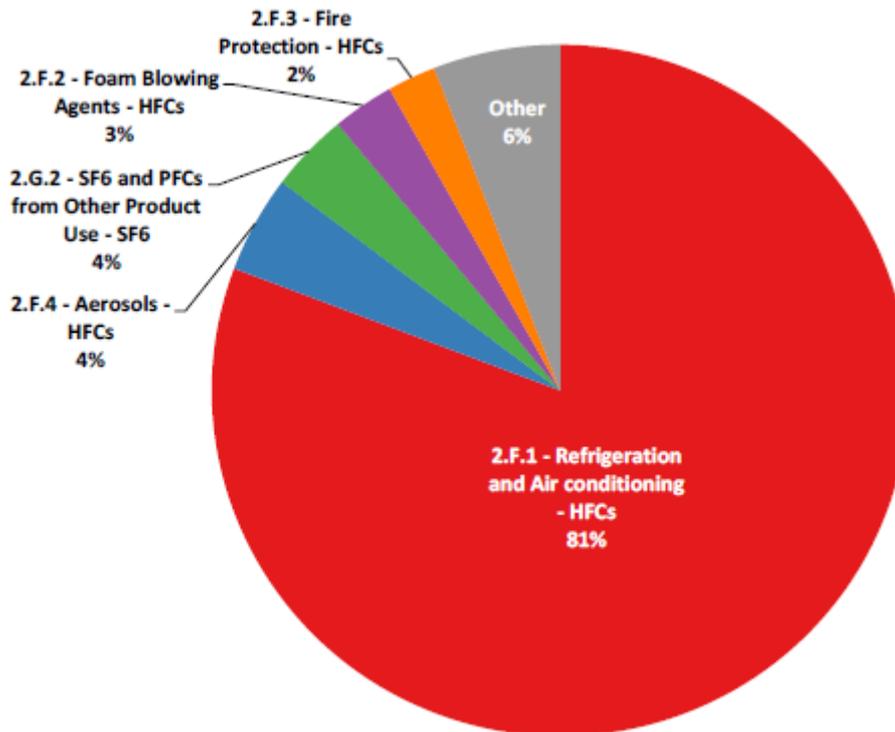


Figure 69: Fluorinated gases emissions' share by source in Europe in 2017 [EEA_19AEUGHG119]

5.2. Implementation of downsizing/rightsizing in Europe

The increasing number of automobiles in Europe, in addition, to their uprising engine displacement and their fuel consumption over the last decades, have force the European Union to establish limits to the manufacturers to decrease these numbers in order to cut down the amounts emissions that were being emitted. According to the European Council [EURO19COT], from the total greenhouse gases emission in Europe in 2016, about 20% were originated in transport, being 94% produced by road transportation and 73% of this produced by light weight vehicles (Passenger cars and vans; 68,62% of all transportation is produced by light weights). From the 90s, the EU has been legislating contamination norms, known as Euro Standards, to reduce the emission of gases produced by automobiles. Among other technics as hybrid engines, which sales share in 2017 was approx. 3% [ACEA18], which One of the most used and successful methods has been downsizing with its improved version so-called rightsizing.

Downsizing and rightsizing of IC engines analysis in aspect of greenhouse gases emission in Europe

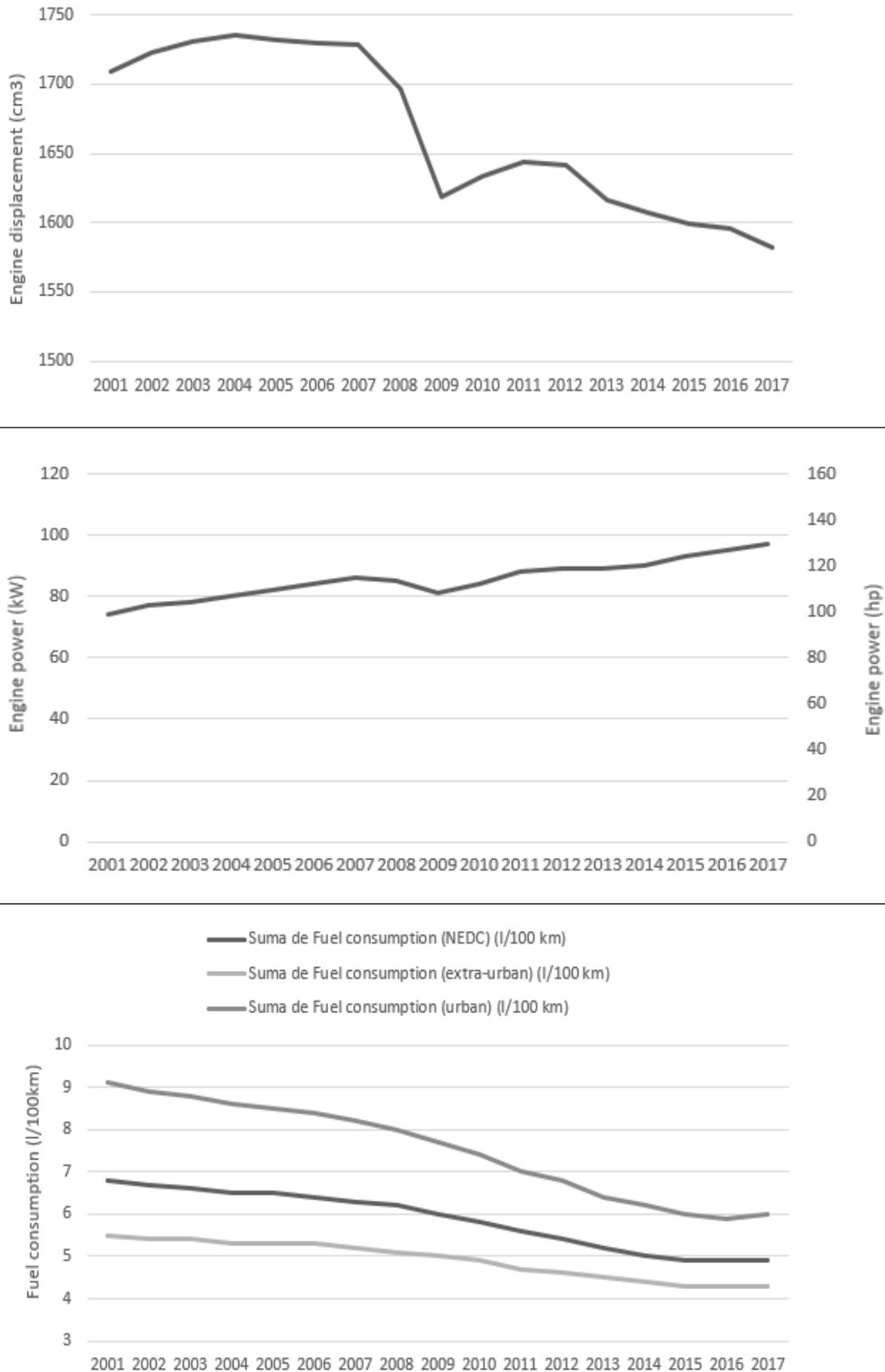


Figure 70: Evolution of engine displacement (Up), engine power (Middle) and fuel consumption (Bottom) from passenger cars in Europe since 2001 till 2017 [ICCT18]

Downsized and rightsized IC engines and greenhouse effect

It is observable the constant decreasing of the engine displacement in the last decade (See *Figure 70, up*), which prove the success of the downsizing technic, from over 1.700 cm³ to just above 1.550 cm³ what involves a total decrease of approx. 10% of engine capacity. The most notorious reduction occurred from 2007 to 2009, where in just two years there was a decrease of around 6%. This important change was as a result of the implementation of the Euro 5 in 2009, which established limits for the emission of volatile organic compounds (VOCs) and particulate matter (PM). Another engine displacement's cutbacks were related to the others EU regulations such as Euro 6 (See *Table 7* and *Table 8*). Although, the considerable decrease of engine capacity, the reduction has not always been as substantial as the first diminution (There was even an increase to 1730 cm³ in the year 2004), due to the establishment of the new technic called rightsizing.

In relation to the power of the engines (See *Figure 70, middle*), this decrement of the engine displacement has derived not in a decrease of the engine power, but in a considerable improvement in it over the years. From the approx. 75 kW (100 hp) in 2001, it has increased to almost 100 kW (130 hp), determining an increase of approx. 25%. This rise of engine power with the reduction of engine displacement, at the same time, confirms the effectiveness of the technologies complementing the internal combustion engine such as supercharging or direct injection.

All the reduction in the engine displacement was originated with the purpose of decreasing the fuel consumption. This relation is shown in the *Figure 70, down*. It represents the progression not only of the overall fuel consumption evaluated with the New European Driving Cycle (NEDC), which has decreased approx. 27%, but also the specific urban and extra-urban consumption. All three values have decreased, but especially the urban consumption with a reduction of 30%, which is the most relevant variable due to its higher values.

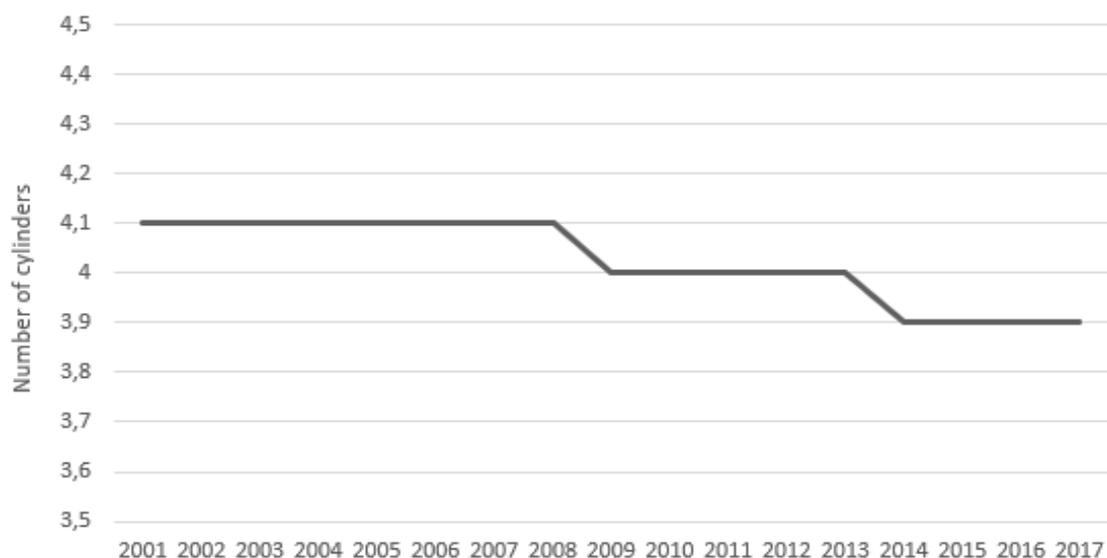


Figure 71: Number of cylinders' progression in passenger cars in Europe from 2001 to 2017 [ICCT18]

Related to the total engine displacement, the average number of cylinders per car has been reduced from 4,1 to 3,9 what represents a decrease of 5%. Then it can be deduced that the average cylinder's size is around 400 cm³ (The highest was 421 cm³ back in 2004) and it has decreased about 5% in 2017 from the year 2001.

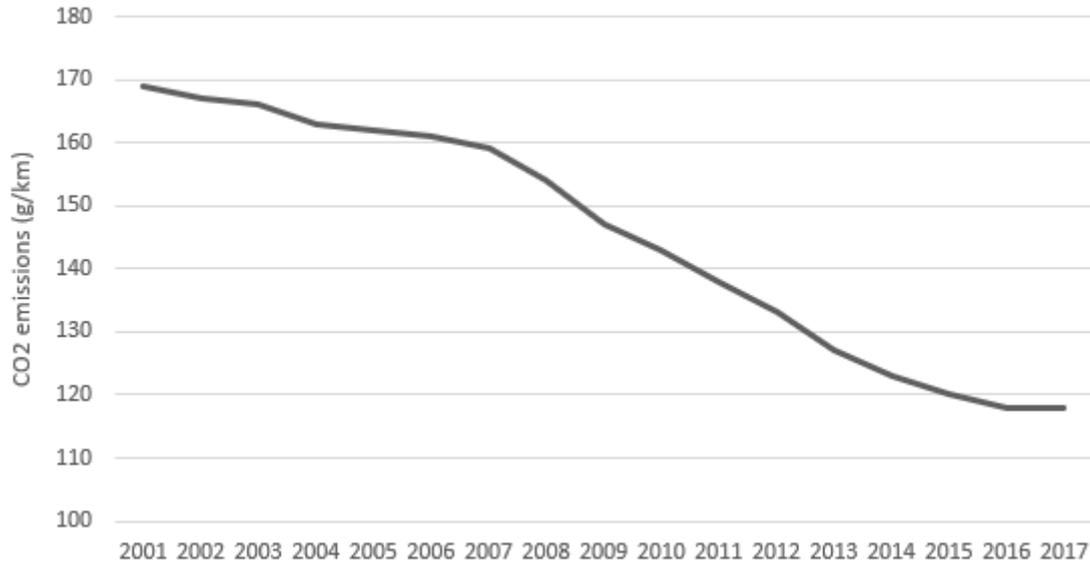


Figure 72: Trend of CO₂ emissions from automobiles in Europe from 2001 to 2017 [ICCT18]

In relation to the progression of the engine emissions, both greenhouse gases (See Figure 72) and pollutants emissions (See Figure 73) have dramatically decreased over the last decades from the 30% of reduction in the most important greenhouse gas, CO₂, (170 g/km in 2001, to under 120 g/km in 2017), to the over 24% of decrease in pollutant emissions (35% including all transport sectors) of carbon monoxide, non-methane organic compounds and particulate matter 2.5 from 2001 till 2017 approx. This decrease in the pollutant emissions can also be observed in the Figure 74, in which is shown that by the year 2017 almost 100% of the cars have already meet all the severe European emission standards.

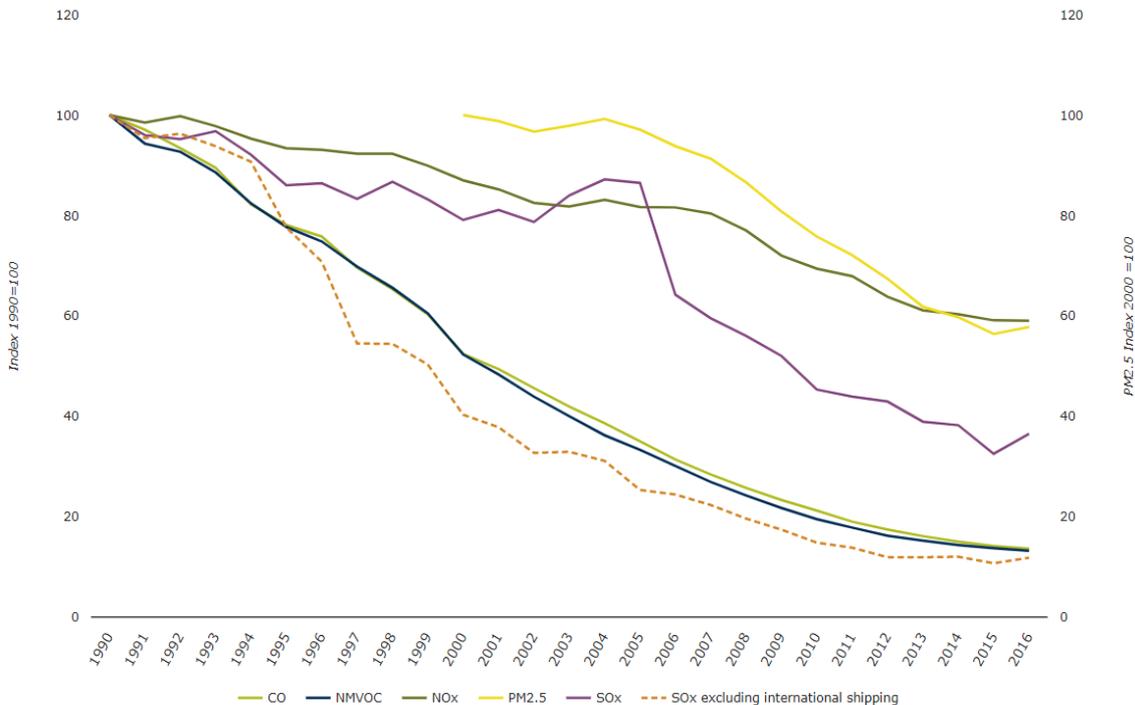


Figure 73: Trends of air pollutants emission from transport in Europe from 1990 to 2016 [EEAC18EAPT]

Downsized and rightsized IC engines and greenhouse effect

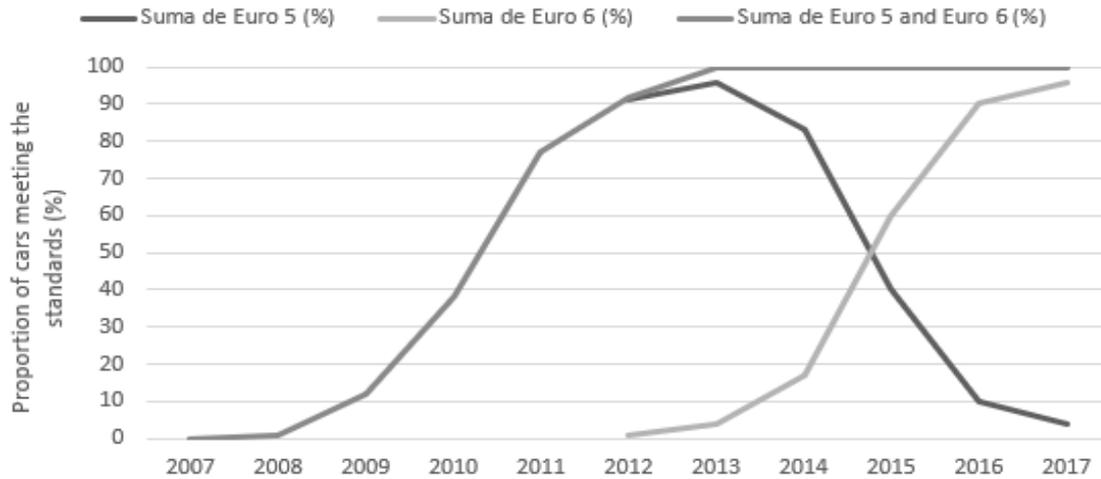


Figure 74: Proportion of cars meeting the European standards of emissions (Euro 5 and Euro 6) from 2007 till 2017 [ICCT18]

Evaluating emissions in depth, a classification of the main manufacturers can be developed based on their sales in 2017 (See Figure 75). The top-ten manufacturers with highest automobiles sales are: Volkswagen, Renault, Ford, Peugeot, Mercedes-Benz, Opel, Audi, BMW, Fiat, Toyota, Citroen and Nissan.

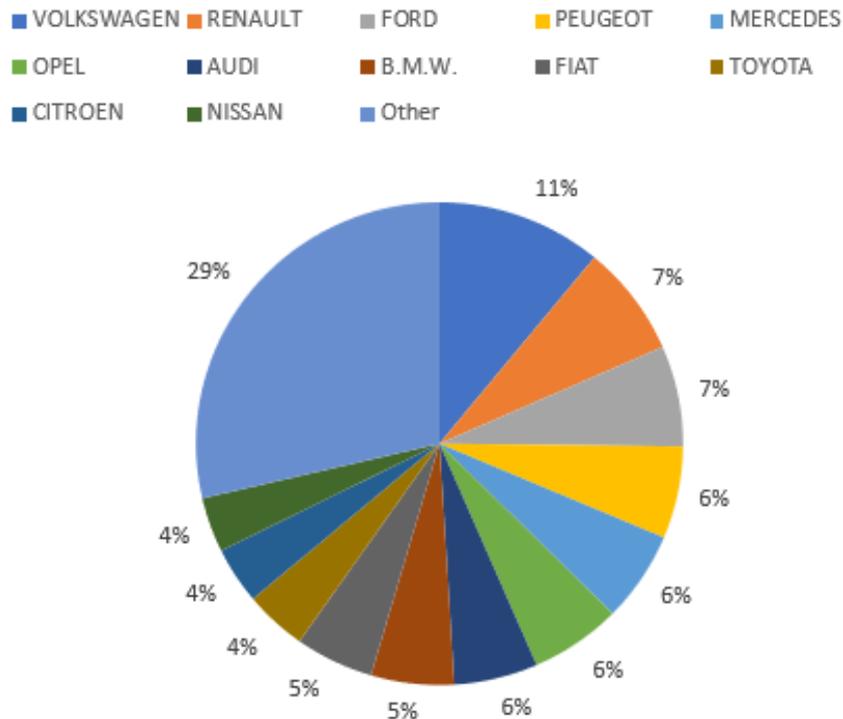


Figure 75: Best selling cars by manufacturing in Europe in 2017 [ACEA19]

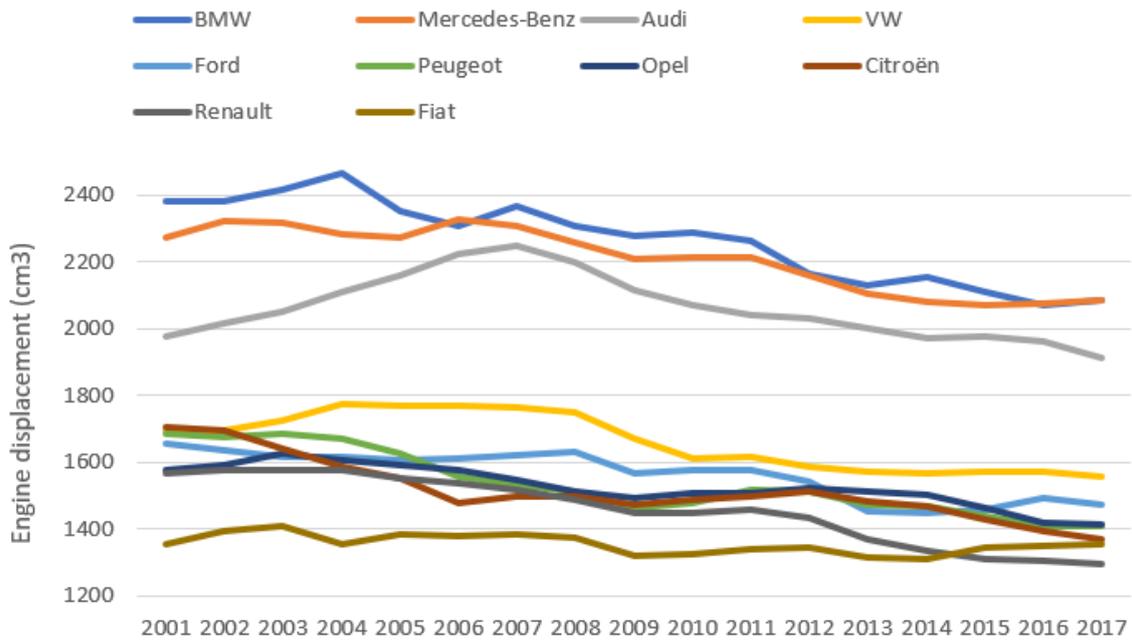


Figure 76: Engine displacement progression of companies with higher sales in Europe in 2017 from 2001 to 2017 [ICCT18]

From the data of Figure 75 and evaluating the information of Figure 76, it can be established that there is a powerful relationship between the best selling companies and their engine displacement, as companies like Volkswagen, Renault and Ford, the three best selling companies in 2017, have a constant decreasing engine capacity over the years, especially in the last decade, where Renault even reach around 1300 cm³ on average in 2017. This support the progression of engine displacement in Europe shown in Figure 70, up.

As shown in Figure 77, the most important manufacturers in Europe have implemented these technologies: 31% of the overall automobiles of these manufacturers have applied turbocharging technologies (Turbo) and over 50% of them have add direct injection (GDI) to their gasoline fuel cars, which are the two main technologies used in the downsizing/rightsizing trend. Furthermore, the Volkswagen company, which belongs to the Volkswagen Aktiengesellschaft Group (VAG) and it is the best-selling company, has almost 100% of GDI models and over 80% of all the models with the turbocharging technology in their cars. These data prove that the downsizing technic is one of the optimal solutions for the immediate future of automobiles' engines.

Downsized and rightsized IC engines and greenhouse effect

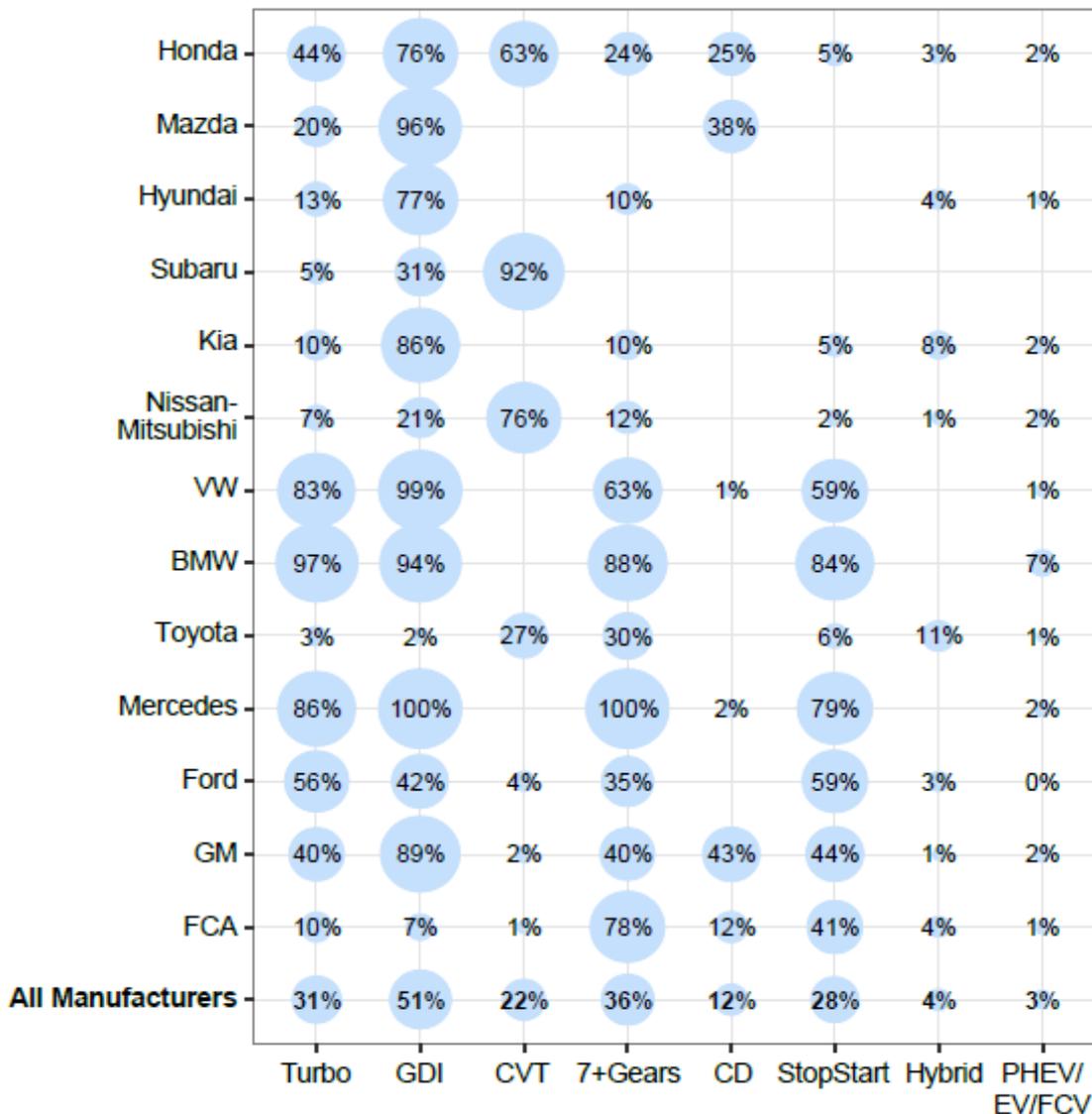


Figure 77: Automobiles manufacturers proportion of use of innovative technologies in 2018 [EPA_19ATR]

Lastly, an analysis of the influence of two important technologies such as variable valve system and gasoline direct injection has been done. In *Figure 78*, two important values of an engine for defining its overall efficiency are compared with these technologies: Specific power, it represents how much power is obtained per unit of engine displacement, and brake specific fuel consumption (BSFC), which declares the relation between the consumption of an engine with its power. Direct injection has not only notoriously increased the specific power to $1,6 \text{ hp/in}^3$ ($1 \text{ in}^3 = 16,39 \text{ cm}^3$), which is an increase in relation to initial fuel charging system, the carburetor, in 1975 of approx. 70%. Additionally, it has decreased the BSFC in about 60% in comparison to the carburetor of 1975. Also, the variable valve system has been an improvement in the specific power, although the BSFC is above the one obtained with traditional fixe and single valve technology. It must be taken into account that the data obtained from the EPA 2018 report in *Figure 78* does not represent the improvements of the technologies isolated: For example, direct injection is commonly added together with turbocharging technology.

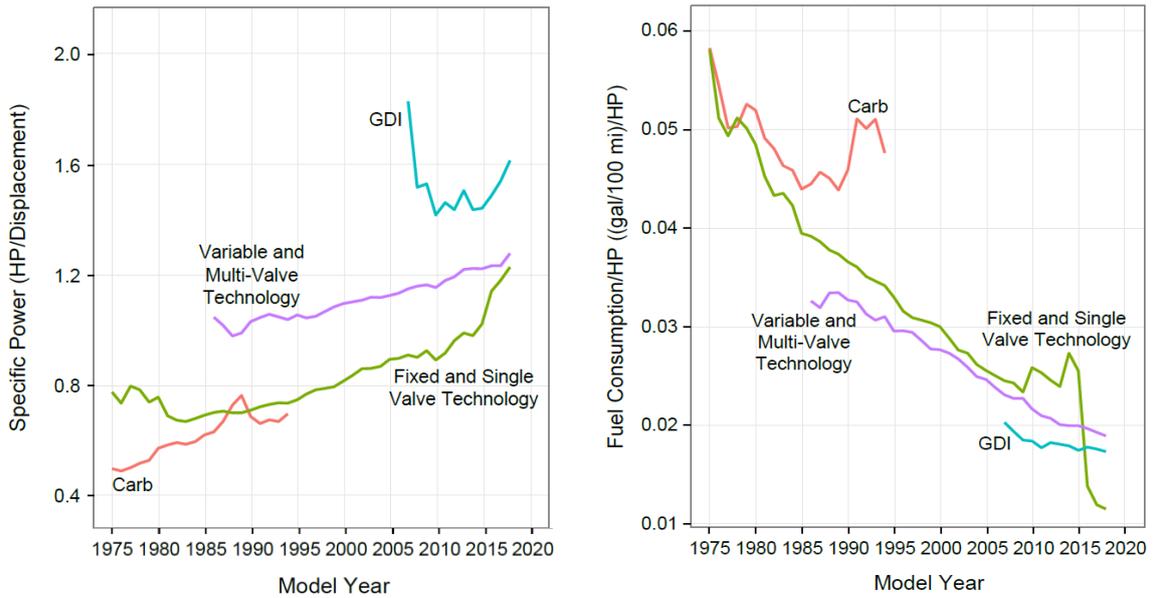


Figure 78: Influence of various engine's technologies in specific power (Left) and brake specific fuel consumption (Right) [EPA_19ATR]

5.3. Downsized engines and greenhouse effect

As established in the analysis of the greenhouse effect, the road transportation sector has been the only sector that has been increasing its emissions in the last three decades, but also in the downsizing analysis it was shown how the emissions of new cars have been decreasing their emissions notoriously. The conclusion of these two facts is that the number of cars in active in the last three decades has been increasing its number of units and its average age, as shown in Figure 79.

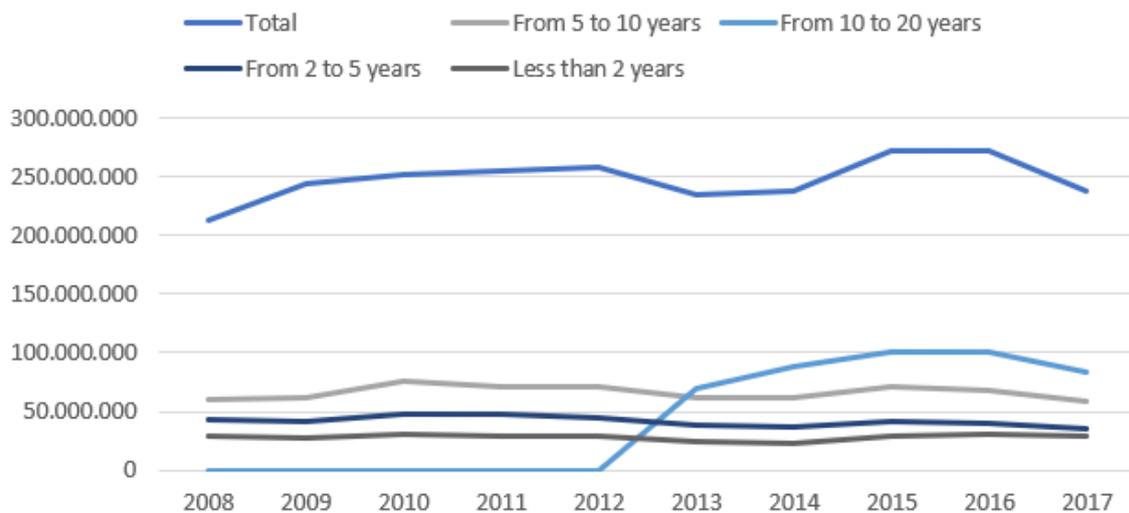


Figure 79: Evolution of the number of active cars according to their age [EURO19PCA]

Downsized and rightsized IC engines and greenhouse effect

6. CONCLUSIONS

- The greenhouse effect is the responsible for the increasing temperatures, especially in the last decades. Although, it is a natural process that permits life in Earth, humans have been enhancing it with their activities resulting in large amounts of emissions of greenhouse gases.
- Greenhouse gases emissions have been decreasing over the last three decades but this decrease has not been enough for preventing the increase of temperatures.
- The human activity sector with higher influence in this effect is the energy one with an approx. 80% of the overall effect.
- The main responsible for this effect is the carbon dioxide, even not the most potent of all the greenhouse gases, it is the one with higher concentrations. Its major contributor is the production of electricity together with the road transportation, when combined they reach over 50% of all the carbon dioxide emissions.
- Road transportation is the only sector responsible for the greenhouse effect which have not decreased its emissions of carbon dioxide and nitrous oxide in the last three decades.
- The progression of engines over the last decades has result in a reduction of the engine displacement of 10%, but an increase of power of 25%. This means that the efficiency of the engines has extremely grow with the downsizing trend.
- The reduction of the engine capacity meant a reduction of 27% in the mixed fuel consumption, a decrease of 30% of the carbon dioxide emissions and a 24% of pollutants emissions in 2016.
- Downsizing associated technologies, turbocharging and direct injection, are introduced in 31% and 51%, respectively, and 83% and 99% in the best selling company, Volkswagen. This shows the high implementation of the downsizing technic.
- If the new car engines have been decreasing their emissions, but the road transportation have been increasing them, the reason is that the number of cars has been increasing and their average age with them.
- The solution for the actual situation of enhanced greenhouse effect, partially caused by the road transportation sector, lies in the expansion of the downsizing trend and the progressive limitation of circulation of old cars with high emission indexes.
- For future investigations a positive development would be the comparison between the downsizing technic, hybrid automobiles and electric ones, considering its advantages in the reduction of emissions, but also their application problems. This should be review in the future due to the lack of use and knowledge of these two new types of technology.

Conclusions

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