POLYTECHNIC OF TURIN
Master of Science in Automotive Engineering

The Diesel Case: Mystification or Subsequent Predestined Decline?
An analysis of the current and future situation throughout Dieselgate and Europe 2020.

Andrea Simonotti

Tutor:
Prof. Paolo Federico Ferrero

To my Parents,
that have always supported me and pushed me
in every step of this adventure
since the very beginning.

To my brother, Dado,
always present even if
always around the world.

To my grandparents, and relatives,
who I could always rely on.

To my historical friends in Rome,
Matteo, Edoardo, Ilaria,
Federica and Marcella...

..but also Cico, Mirty and Gabro.

To my flatmate and friend,
Gerard, for bearing me every day.

To my Tutor in FIAT, Luca Marengo,
and all my colleagues,
that have welcomed me
as a part of the team.

To my professor Paolo Ferrero,
for helping me in the creation of this work.

And to all my friends, in Italy and abroad,
for being part of the path
that led me to where I am today.

Table of Contents

List of Figures:

List of Tables

Abbreviations

AF	Alternative Fuel
ASTM	American Society for Testing and Materials International
BDC	Bottom Dead Centre
BEV	Battery Electric Vehicle
CFC	Chlorofluorocarbons
CFR	Cooperative Fuel Research
CNG	Compressed Natural Gas
DPF	Diesel Particulate Filter
E85	Petrol Containing 85% Ethanol
ECE	Urban Driving Cycle
EEA	European Environmental Agency
EFTA	European Free Trade Association
EGR	Recycling of Gas Exhaust
EPA	Environmental Protection Agency
EUDC	Extra Urban Driving Cycle
EUGT	Environment and Health in the Transport Sector
EU28	28 European Countries
FCEV	Fuel Cells Electric Vehicle
FDP	Fossil Resource Depletion
FTP	Federal Test Procedure
FY	Full Year
GISS	Goddard Institute for Space Studies
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HB	Hatchback
HC	Hydrocarbons
HDV	Heavy Duty Vehicle
ICE	Internal Combustion Engine
KW	Kilowatt
LCV	Light Commercial Vehicle
LDT	Light Duty Truck
LDV	Light Duty Vehicle
LNT	Lean NOx Trap
LPG	Liquefied Petroleum Gas
MY	Model Year
NCDC	National Climatic Data Centre
NEDC	New European Driving Cycle
NOx	Nitrogen Oxide
PAH	Polynuclear Aromatic Hydrocarbons
PHEV	Plug In Hybrid Vehicle
PM	Particulate Matter
RDE	Real Driving Emissions
RPM	Revolutions per Minute
R&D	Research and Development
SCR	Selective Catalytic Reduction
SFTP	Supplementary Federal Test Procedure
SW	Station Wagon
TCO	Total Cost of Ownership
TDC	Top Dead Centre
YTD	Year To Date
WLTP	World Harmonised Light Vehicle Test Procedure

Executive Summary

"If we want everything to remain the same, everything must change"

Il Gattopardo, Giuseppe Tomasi di Lampedusa, 1958

It is easy for people to remain in their comfort zone, enjoying the pleasure of the status quo, not worrying about the future consequences of their actions.
Unfortunately the events of the last years are forcing us to open our eyes and re-think about our choices. The frantic rhythm of life, people are used to nowadays, have proved to be energetically unsustainable, leading to an irreversible climate change whose consequences are impossible to ignore.
In this optic, transportation systems, along with energy generation, are playing a major role in the pollution increase and ended up in the eye of the storm of the public opinion.

The new millennium opened up right in the middle of the steady growth of car industry, driven by the promises of freedom and self-satisfaction intrinsically connected. The sector experienced a state of continuous growth, that not even the economic crisis could stop, thanks to the sudden motorization of China, that in more than a decade became the first global market, far above 20 million units per year.

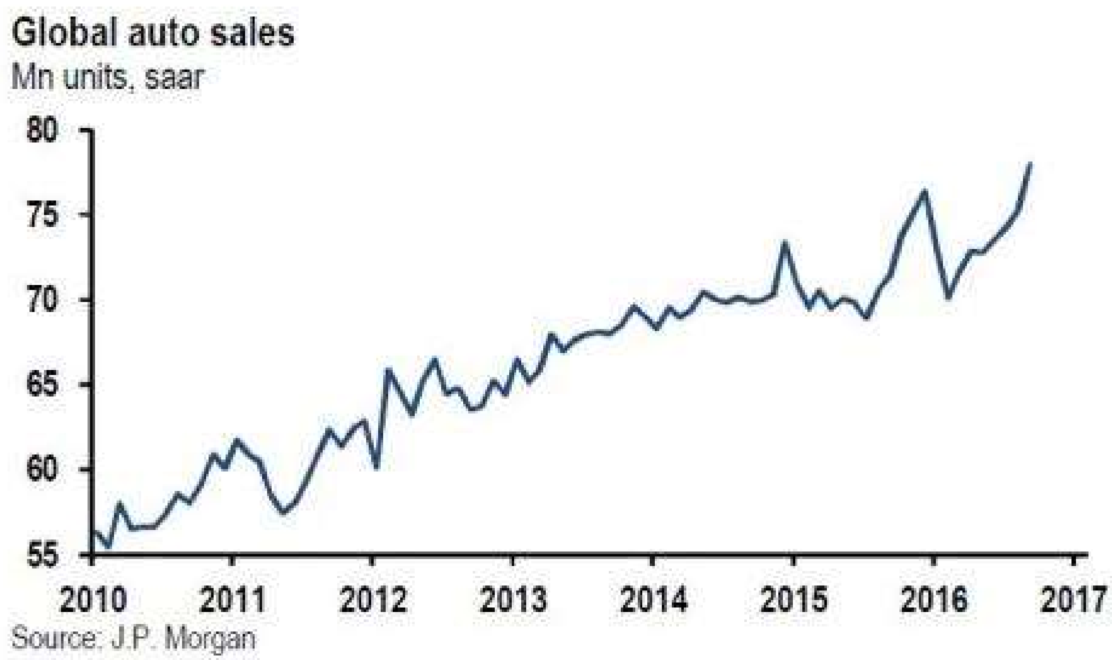


Figure 1: Global Auto Sales 2010-2017

The question rises, what are we heading to? On one hand, people are not willing to give up to their actual way of life, on the other hand, the world is strongly asking for a green revolution leading to an equilibrium that could not mine the future survival of the humankind.
The famous sentence, said by Tancredi in "Il Gattopardo" that opened this thesis, is the perfect exemplification of the current situation. Car Industry is living one of the biggest transformation of the last 50 years, calling into question all the basis taken for granted in the last years.

Much of this transformation is pushed by the institutions, that forced the environmental moral into an economically driven sector. The new regulations that are to be implemented in EU by all automakers starting from 2020 (Chapter 4, Chapter 6), are obliging all carmakers to re-think their engines choices, in order to achieve standards almost impossible to reach with the current technology.

At the same time, we are living right in this years, one of the biggest scandal of the sector, strictly connected with the topic of environment and pollution: the Dieselgate (Chapter 7). The issue is very critical but at the same time easily misunderstandable by the masses, that confuse it with the mere not-realistic results of the homologation cycles. The latter are being modified right now in order to achieve results clear and compliant with reality (Chapter 5).
The "sudden" discover of the cheat in the emission testing of the Volkswagen group regarding diesel engines, soon turned into a global prosecution towards diesels as a whole, with drastic consequences, both from the perspective of the institutions (Chapter 8) and the market (Chapter 9): markets' trends will be analyzed with a particular focus on the European market.

As a consequence, markets have started to change, and all major manufacturers are following the trend in order to provide customers with products desirable and compliant with regulations.
Another big driver of the process is the rise of electric cars, in the form of hybrids, hybrids plug-in and full EV, that are presented to the markets are the perfect green solution for a better future.
But what is the truth behind? Is it really electricity the only solution to combustion engines, or this obstinacy against Diesel in particular is unfounded?

To answer these intricate and knotty questions, this work starts with a brief recap of the former history of Diesel engines (Chapter 1) followed by an analysis of the chemical of fuels (Chapter 2) and the relative pollutant (Chapter 3) in order to provide the basis for the final considerations (Chapter 10).

1. THE HISTORY OF DIESEL ENGINE

1.1 Rudolf Diesel' Invention

The Diesel engine takes its name after, Rudolf Diesel, who was born in Paris, France in 1858. His invention came while the steam engine was the predominant power source for large industries, led by the willingness of finding an alternative and more efficient way to provide energy to power factories.

Figure 2: Rudolf Diesel (1858-1913)

In 1885, Diesel set up his first shop in Paris to begin development of a compression ignition engine. The process would last 13 years. In the 1890s, he received a number of patents for his invention of an efficient, slow burning, compression ignition, internal combustion engine. From 1893 to 1897, Diesel further developed his ideas at Maschinenfabrik-Augsburg AG (later Maschinenfabrik-Augsburg-Nürnberg or MAN). In addition to MAN, Sulzer Brothers of Switzerland took an early interest in Diesel's work, buying certain rights to Diesel's invention in 1893.

At MAN in Augsburg, prototype testing began with a 150 mm bore/400 mm stroke design on August 10, 1893. On February 17, 1894, the redesigned engine ran for 88 revolutions - one minute; with this news, Maschinefabrik Augsburg's stock rose by 30%, indicative of the tremendous anticipated demands for a more efficient engine.

In an internal-combustion engine, the combination of a cylinder and piston constructed and arranged to compress air to a degree producing a temperature above the igniting-point of the fuel, a supply for compressed air or gas; a fuel-supply; a distributing-valve for fuel, a passage from the air supply to the cylinder in communication with the fuel-distributing valve, an inlet to the cylinder in communication with the air-supply and with the fuel-valve, and a cut-oil, substantially as described.

Extract of Diesel' 1895 Patent

While the first engine test was unsuccessful, a series of improvements and subsequent tests led to a successful test on February 17, 1897 when Diesel demonstrated an efficiency of 26.2% with the engine. The first Sulzer-built diesel engine was started in June 1898.

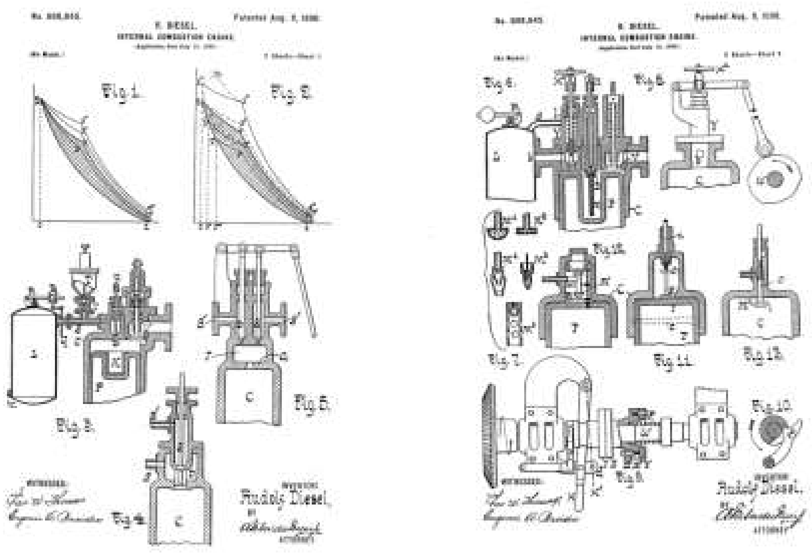


Figure 3: Image Patented Aug. 9, I898. R. DIESEL: Internal Combustion Engine.

Development of Diesel’s invention needed more time and work to become a commercial success. Many engineers and developers joined in the work to improve the market viability of the idea created by Rudolf Diesel. He, on the other hand, became somewhat threatened by this process and was not always able to find common language with other engine designers developing his invention. Diesel’s attempts of market promotion of the not-yet-ready engine eventually led into a nervous breakdown, that eventually brought the inventor to commit suicide. This happened even if by 1898 he had become a millionaire. His engines were used to power pipelines, electric and water plants and marine craft. They were soon to be used in mines, oil fields, factories, and transoceanic shipping.

After Diesel’s patents started to expire, a number of other companies took his invention and developed it further.

The evolution of Diesel engines technologies is due to the works of engineers like George Brayton, Herbert Akroyd Stuart; Richard Hornsby and Sons, Thomas Henry Barton, Herbert Akroyd Stuart.

1.2 Charles Wallace Chapman first Diesel Engine for Cars

The first real application of a Diesel engine to a car happened thanks to British engineer Charles Wallace. On 7 June 1932 he jointly founded Perkins Engines in Peterborough, together with his former friend Frank Perkins, led by the common idea of bringing the technology of Diesel engine to mass transportation. Up until this date, diesel engines had been large, low-revving monsters, mainly used for marine, railway and agricultural applications.

The first engine, **dubbed Vixen**, was complete by December 1932. It was the world's first high speed diesel engine. Perkins' first years were faltering ones. The successful Wolf engine of 1934 brought in orders, but a tax on diesel fuel the following year nearly finished the company off. Instead, it managed to diversify into engines for larger trucks as well as farming, industrial and marine applications. It also came up with some novel publicity coups including installing a Wolf engine in a racing car and setting new speed records at the banked Brooklands' circuit in Surrey. A peak speed of almost 95mph was recorded, impressive performance for any vehicle of the era, let alone something powered by a diesel.

One of Charles' Chapman's greatest creations came along in 1936, with the six-cylinder P6 engine, widely regarded as years ahead of its time.

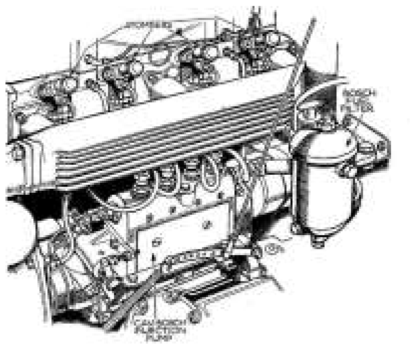


Figure 4: Perkins diesel engine

1.3 First Diesel Cars

It was until 1912 that the first train with a diesel engine was introduced by the Danish. In 1922 the first land vehicle without a track, a tractor by Mercedes-Benz was built with a diesel engine. Finally, in 1923, the first truck with a diesel engine was introduced by Daimler, Benz and MAN.

The Cummins "Diesel Special" race car was driven at both Daytona and the Indianapolis 500 in 1931 and did not have to make a single pit stop. In 1933 an older Bentley fitted with a diesel engine was the first of its kind to compete in the Monte Carlo Rally. In 1934, the Diesel Cummins Indy Car made another appearance (both are pictured above).

Production diesel car history started in 1933 with **Citroën's Rosalie**, which featured a diesel engine option (the 1,766 cc) in the Familiale. The Rosalie 10 DI engine had an output of 40HP at 3.650 rpm. It was a 4 cylinder engine with 75/100 bore/stroke ratio. Because of legal restrictions on the diesel engine, the car did not go into production until 1935, when several dozen cars were built and proved reliable in a daily use. Citroen officially introduces its diesel Rosalie to the Paris Motor Show 1936.

Between 1934-1939 about 3000 of Diesel Ricardo-Citroen engines were produced equipping commercial vehicles. Thanks to this system of injection, having proven reliable and with the “suspended” assembly of the engines used as a European pioneer by Citroen, these Diesel cars reached speeds close to that of the gasoline car engines at 3500RPM. They moreover were regarded as comfortable models, in particular, thanks to the little vibrations transmitted to the cockpit.

Figure 5: Citroen Rosalie Familiale Diesel

Shortly afterward, in 1936 the **Mercedes-Benz 260D** and the Hanomag Rekord diesel cars were introduced into the marketplace.
It employed the Bosch diesel fuel injection system and produced 45 bhp (34 kW) at 3000 rpm. The car weighed approximately 1,530 kg (3,373 lb) and could attain a top speed of 95 km/h (59 mph).
Although similar in styling to its gasoline counterparts, what set the 260D apart was its fuel consumption, 9 litres per 100 kilometres, compared to gasoline engine's 13 litres per 100 kilometres. As if that wasn't enough to spark consumer's interest, at the time of the 260D's introduction, diesel cost less than gasoline, but not by a small margin, the cost of diesel was less

than half the cost of gasoline, a sure sign of the cost effectiveness of owning a diesel-powered vehicle.

Because of the size and weight of the diesel engine, however, they did not flourish in the automotive industry like gasoline powered cars did

Nearly 2,000 vehicles were assembled until 1940, after which the Daimler-Benz group had to devote itself almost entirely to military manufacture.

Over the next few years, the Mercedes 260D was replaced with new and improved versions and benefited from numerous upgrades, but in the end, the 260D will always be remembered for one thing: it was the world's introduction to the many benefits a diesel-powered passenger car had to offer.

Figure 6: Mercedes-Benz 260D

1.4 Definitive Growth of Diesel

In the 1950s and 1960s diesel cars were slowly re-introduced to the public on a limited basis. Mercedes-Benz, Peugeot, Austin, Isuzu, Fiat, and several others began introducing diesel driven taxis, ambulances, station wagons and a few other autos.

In 1967, Peugeot introduced the world's first compact, high-speed diesel car, the Peugeot 204BD with 1.3 L XL4D engine that produced 46 PS (34 kW) at 5,000 rpm.

Following the 1970s oil crisis (1973 and 1979), Volkswagen introduced their first diesel, the VW Golf, with a 1.5 L naturally aspirated indirect-injection engine which was a redesigned (dieselised) version of a gasoline engine. Since this time, turbo charged, fuel injected diesel engines and low emissions diesel cars have hit the market.

Mercedes-Benz tested turbodiesels in cars (e.g. by the Mercedes-Benz C111 experimental and record-setting vehicles) and the first production turbo diesel cars were, in 1978, the 3.0 5-cylinder 115hp (86 kW) Mercedes 300 SD, available only in North America, along with the Peugeot 604.

The biggest single step forward for mass-market diesel cars came in 1982 when PSA Peugeot Citroën introduced the XUD engine in the Peugeot 305, Peugeot 205 and Talbot Horizon. This was one of the class leading automotive diesel engine until the mid-1990s.

Further improvements of the performances of Diesel engines took place thanks to the adoption of a direct injection system, first marketed by Fiat with the 1986 Fiat Croma Turbo D.

Figure 7: Fiat Croma TD

The first mass market turbo diesel was the XUD powered, 1988 Citroën BX and then the 1989 Peugeot 405, they gave power and refinement approaching petrol engine standards, starting to turn Diesel into a real and feasible alternative.

In 1996 Fiat Group, with the Alfa Romeo 156 2.4 JTD, presented its new original invention, the Common-Rail (direct fuel injection system for diesel engines), that would have become in the following years the basis of modern Diesel Engines. The main advantage of the common-rail system is its ability to vary injection pressure and timing over a broad scale. This is made possible by separating the functions of pressure generation and fuel injection. Its offered a significantly higher level of adaptability to engine design on the part of the fuel-injection system as evidenced by its:

- wide range of applications (cars, light commercial vehicles, heavy-duty trucks, railway locomotives and ships)
- high injection pressures (up to approx. 1,600 bar)
- variable injection timing

- capability of multiple pre- and post-injection phases (even extremely retarded post-injection is possible)
- variation of injection pressure (230...1,600 bar) according to engine

By selling the patent to Bosch, Fiat made the technology available to all the competitors, allowing a further widespread of this engines all over the market.

In the following years all the cars manufacturers in Europe invested big amounts of money in research in order to provide their cars with the most modern Diesel engines, following a positive trend of the market.

Figure 8: 4 Cylinders Diesel Engine

Customers kept asking for more efficient cars able to deliver the same performances of equivalent Petrol with less fuel consumption: that was basically the main reason of the success of Diesel engine powered cars.

2. CHEMICAL OF DIESEL FUELS

Diesel fuels are distilled from crude oil by boiling point by a process called fractional distillation.

Petrol is produced at temperature between 35 degrees to 200 degrees while diesel is produced at a boiling point of 250-350 degrees. After distillation, in order to use these by-products as commercially acceptable petrol and diesel, some blending with other elements has to be done. Petrol is produced first in this process as it is produced at a lower temperature than diesel.

Diesel is composed of about 75% by saturated hydrocarbons (primarily paraffin's including n, iso, and cycloparaffins), and 25% aromatic hydrocarbons (including naphthalene's and alkyl benzenes). They all have boiling points in the range 160-380 °C (middle distillates). Diesel fuel ignites on average at approximately 350 °C, which is very early in comparison with gasoline (500 °C, lower limit for Diesel fuel is 250 °C). In order to cover the growing demand for diesel fuels, the refineries also add "conversion products", i.e. thermal and catalytic-cracking products.

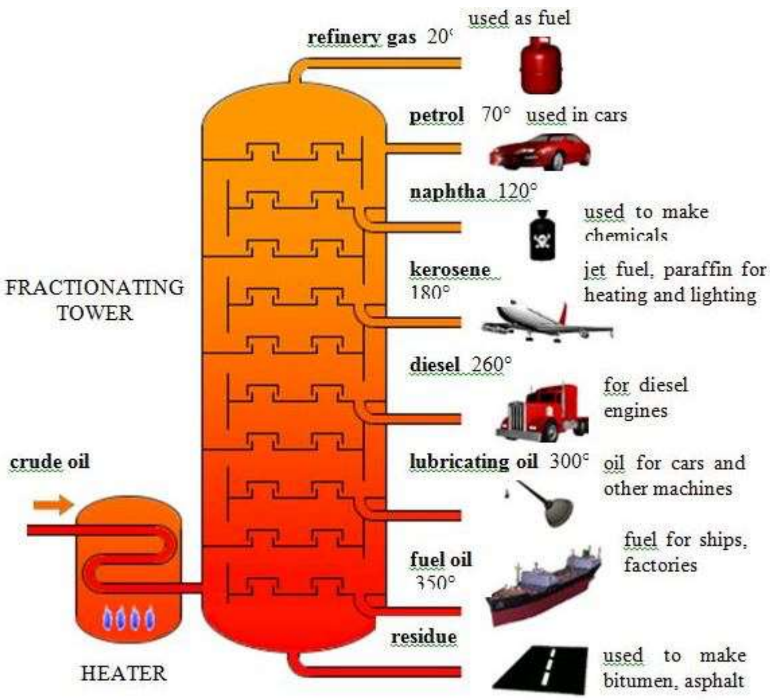


Figure 9: Fraction Distillation

The average chemical formula for common diesel fuel is C12H23, ranging from approx. C10H20 to C15H28, while Petrol consists of hydrocarbons with between 5 and 12 carbon atoms per molecule but then it is blended for various uses.

The empirical formula for diesel is $C_{12}H_{23}$. That means for every 12 moles of carbon in a given amount of diesel there are 23 moles of hydrogen. This formula does not tell us the structure of diesel, because it is not a structural formula, it is an empirical formula. Since Diesel is made up of a mixture of hydrocarbons it is needed to consider the weighted average of amount of carbon and hydrogen, so it turns out that the formula for diesel is C12H23.

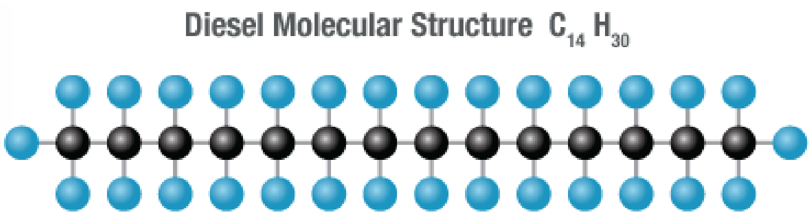


Figure 10: Molecular Structure of Diesel Fuel

The macroscopic properties of diesel are also important in order to understand how the diesel engine works. The macroscopic properties of diesel are governed by the intermolecular forces of diesel. The only intermolecular force in diesel is the London dispersion force because hydrocarbons are all non-polar. Since diesel molecules are relatively large, its intermolecular forces play a big role. Diesel can become very viscous in the cold environments. Engines are usually designed for the fuel having one viscosity, so this can be a major problem.

Other properties of diesel fuel that are important are flash point and auto ignition temperature. Diesel has a high flash point which is a safety factor. Flash point is the lowest temperature that the fuel can form an ignitable temperature with air at. Since diesel has a high flash point it does not burn as easily as gasoline. Diesel also has a low auto ignition temperature, which means it will ignite without any external actions, such as a flame or a spark. This is why diesel engines do not need a spark plug. The auto ignition temperature of diesel ranges from 177-329 degrees Celsius depending on the type of diesel you are using.

2.1 Cetane Number

Cetane number is the measure of the tendency of the fuel to ignite spontaneously.

The cetane number test method for diesel fuel was developed in the 1930s by the Cooperative Fuel Research, CFR, committee and later standardized by ASTM. The cetane number scale is defined by two specific: 1-methylnaphthalene (also called a-methylnaphthalene), that, since it burns poorly in a diesel engine, was assigned a cetane number of zero and n-hexadecane (cetane, that on the other hand burns well, was assigned a cetane number of 100. These hydrocarbons represent the primary reference fuels for the method. The cetane number of a fuel is defined as the volume percent of n- hexadecane in a blend of n-hexadecane and 1-methylnaphthalene that gives the same ignition delay period as the test sample. For example, a fuel with a cetane number of 60 will perform the same in the engine as a blend of 60% n-hexadecane and 50% 1-methylnaphthalene.

In 1962, the low cetane number primary reference fuel was replaced because 1-methylnaphthalene had been found to be kind of unstable, expensive, and difficult to use in the CFR engine. The new reference fuel is the 2,2,4,4,6,8,8-heptamethylnonane (sometimes called isocetane). When measured against the two original primary standards, 2,2,4,4,6,8,8-heptamethylnonane has a cetane number of 15. Along with it, also the equation used to calculate cetane number was modified to keep the cetane number scale the same.

In the cetane number scale, high values stand for fuels that ignite readily and as a consequence, perform better in a diesel engine. Concerning Petrol engine instead, in the octane number scale, high values represent fuels that resist spontaneous ignition and, therefore, have less tendency to knock in a gasoline engine. It is worth noticing that both scales were developed so that higher numbers represent higher quality for the respective use, high cetane number fuels have low octane numbers, and vice versa.

High -quality diesel fuels are characterized by the following features:

- High cetane number
- Relatively low upper boiling limit
- Narrow density and viscosity spread
- Low aromatic compounds (particularly polyaromatic compounds) content
- Low sulphur content (< 10 ppm)

In addition, the following characteristics are particularly important for the service life and consistent function of fuel-injection systems:

- Good lubricant qualities
- Absence of free water
- Low dirt content

2.2 Biodiesel

Biodiesel is an alternative fuel similar to conventional or 'fossil' diesel. Biodiesel can be produced from straight vegetable oil, animal oil/fats, tallow and waste cooking oil. The process used to convert these oils to Biodiesel is called transesterification. The largest possible source of suitable oil comes from oil crops such as rapeseed, palm or soybean. In the UK rapeseed represents the greatest potential for biodiesel production. Most biodiesel produced at present is produced from waste vegetable oil sourced from restaurants, chip shops, industrial food producers such as Birdseye etc. Though oil straight from the agricultural industry represents the greatest potential source it is not being produced commercially simply because the raw oil is too expensive. After the cost of converting it to biodiesel has been added on it is simply too expensive to compete with fossil diesel. Waste vegetable oil can often be sourced for free or sourced already treated for a small price. (The waste oil must be treated before conversion to biodiesel to remove impurities). As a result, Biodiesel produced from waste vegetable oil can compete with fossil diesel.

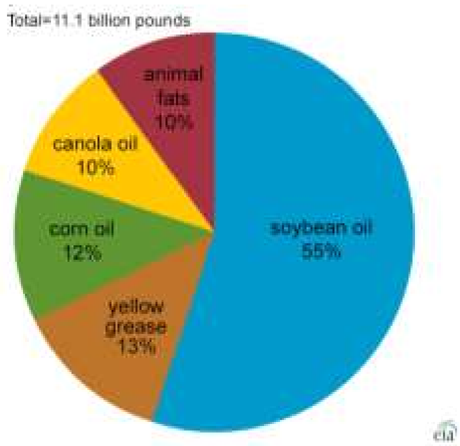


Figure 11: Feedstock inputs to U.S biodiesel production, 2016

Biodiesel has many environmentally beneficial properties. The main benefit of biodiesel is that it can be described as 'carbon neutral'. This means that the fuel produces no net output of carbon in the form of carbon dioxide (CO2). This effect occurs because when the oil crop grows it absorbs the same amount of CO2 as is released when the fuel is combusted. In fact this is not completely accurate as CO2 is released during the production of the fertilizer required to fertilize the fields in which the oil crops are grown. Fertilizer production is not the only source of pollution associated with the production of biodiesel, other sources include the esterification process, the solvent extraction of the oil, refining, drying and transporting.

All these processes require an energy input either in the form of electricity or from a fuel, both of which will generally result in the release of greenhouse gases. To properly assess the impact of all these sources requires use of a technique called life cycle analysis. Biodiesel is rapidly biodegradable and completely non-toxic, meaning spillages represent far less of a risk than fossil diesel spillages. Biodiesel has a higher flash point than fossil diesel and so is safer in the event of a crash.

On the other hand it produces more emissions of nitrogen oxide (NOx) than diesel, a problem that can be contained by redesigning diesel engines and providing the exhaust with special catalysts.

From a socio-environmental point of views some negative points have been carried out in the last years as

- Use of arable land not for purchase.
- Raising the price of raw materials in Third World countries. Among the problems is to create food insecurity.

- If cultivation techniques are monocultures, this reduces biodiversity, increases soil erosion and the risk of insects and bacteria that destroy crops.

Figure 12:Soybean Oil

2.3 Basics of Diesel Cycle.

Diesel cycle is one of most common thermodynamic cycles that can be found in automobile engines and describes the functioning of a typical compression ignition piston engine. The Diesel engine is similar in operation to the gasoline engine. In an ideal Diesel cycle, the system executing the cycle undergoes a series of four processes: two isentropic (reversible adiabatic) processes alternated with one isochoric process and one isobaric process

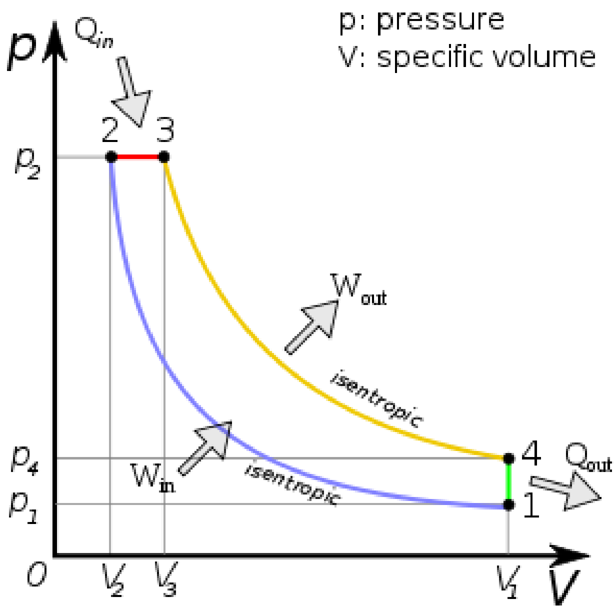


Figure 13: Phases of Diesel Cycle P-V Diagram

Process 1-2: Isentropic Compression

In this process, the piston moves from Bottom Dead Centre (BDC) to Top Dead Centre (TDC) position. Air is compressed isentropically inside the cylinder. Pressure of air increases from p1 to p2, temperature increases from T1 to T2, and volume decreases from V1 to V2. Entropy remains constant (i.e., s1 = s2). Work is done on the system in this process (denoted by Win in the diagrams above).

Process 2-3: Constant Pressure Heat Addition

In this process, heat is added at constant pressure from an external heat source. Volume increases from V2 to V3, temperature increases from T2 to T3 and entropy increases from s2 to s3.

Process 3-4: Isentropic Expansion

Here the compressed and heated air is expanded isentropically inside the cylinder. The piston is forced from TDC to BDC in the cylinder. Pressure of air decreases from p3 to p4, temperature decreases from T3 to T4, and volume increases from V3 to V4. Entropy remains constant (i.e., s3 = s4). Work is done by the system in this process (denoted by Wout in the p-V and T-s diagrams above).

Process 4-1: Constant Volume Heat Rejection

In this process, heat is rejected at constant volume (V4 = V1). Pressure decreases from P4 to P1, temperature decreases from T4 to T1 and entropy decreases from s4 to s1.

$$\eta_{\text{Diesel}} = 1 + \frac{Q_L}{Q_H} = 1 + \frac{C_v(T_1 - T_4)}{C_p(T_3 - T_2)} = 1 - \frac{T_1}{\gamma T_2}\frac{(T_4/T_1 - 1)}{(T_3/T_2 - 1)}.$$

2.3.1 Otto Cycle vs. Diesel Cycle efficiency

Otto Cycle

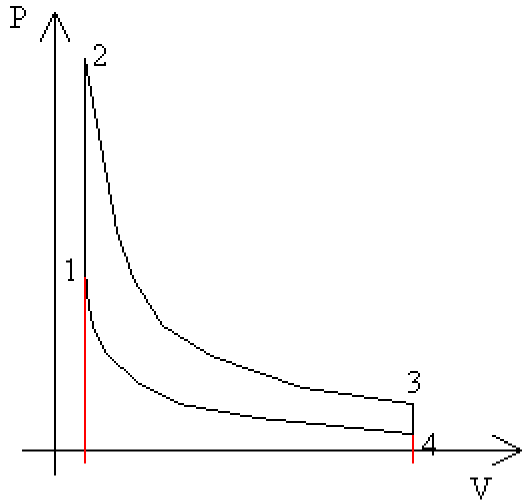


Figure 14: Otto Cycle

Has an efficiency: $$\eta = \frac{1}{r^{1-\gamma}}$$

Where $r = \frac{V3}{V1}$ is defined as Compression Ratio.

Diesel Cycle

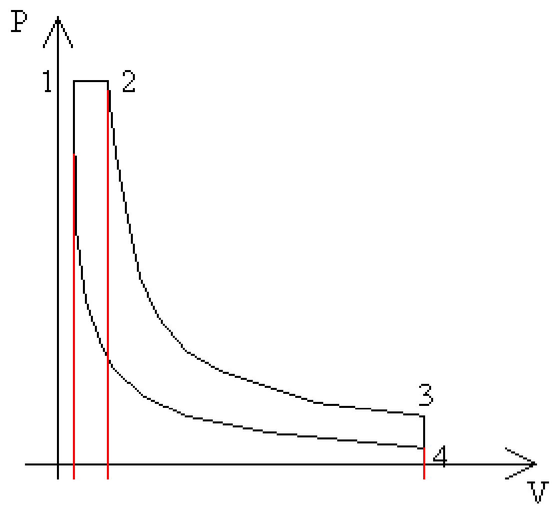


Figure 15: Diesel Cycle

Has instead an efficiency defined, alternatively, as:

$$\eta = 1 - \frac{1}{\gamma} \frac{\left(\frac{1}{r_e}\right)^{\gamma} - \left(\frac{1}{r_c}\right)^{\gamma}}{\frac{1}{r_e} - \frac{1}{r_c}}$$

where $Rc = \frac{V2}{V1}$ and $Re = \frac{V2}{V3}$ are defined as compression ratio related to temperature.

g = adiabatic constant (Cp/Cv) that for unburned gas is equal to 1,2

It is worth noticing that with the same compression ratio, the efficiency of the Otto Cycle is much higher than the one of the Diesel Cycle, as shown in the following table.

V3/V1	H Otto	H Diesel
7,0	0,32	0,29
8,0	0,34	0,31
9,0	0,36	0,33
10,0	0,37	0,34
11,0	0,38	0,35
12,0	0,39	0,36
13,0	0,40	0,37
14,0	0,41	0,38
15,0	0,42	0,39
16,0	0,43	0,40
17,0	0,43	0,41
18,0	0,44	0,41
19,0	0,45	0,42
20,0	0,45	0,43
21,0	0,46	0,43
22,0	0,46	0,44
23,0	0,47	0,44
24,0	0,47	0,45
25,0	0,47	0,45

Table 1. Efficiency Comparison, Otto and Diesel

However, the Otto cycle can rarely exceed a compression ratio of 1/10 to avoid self-ignition that occurs during a compression phase.

The Diesel cycle, on the other hand, needs self-ignition, as far as only air is compressed and there is no risk of auto-ignition of the fuel. Combustion is ideal between points 1 and 2 of the diagram. A great compression ratio for a Diesel is around 1/22.

As can be seen from the table, the theoretical maximum efficiency is therefore 44% against 37% of the Otto cycle.

However, let us not be fooled by these flattering performance values. The real cycles are far from following exactly the theoretical tracks especially at high revs. The engine must also power the internal services (valve movement, lubrication, circulation of refrigerant fluid, etc.) and external (lights, air conditioner, radio, etc..). Real efficiency rates therefore amount to far more modest 25% for a Diesel and below 15% for a petrol engine.

In the following table are listed some of the main real performance indicators of both Otto and Diesel engines.

					Rated maximum				
	Operating cycle	Compression ratio	Bore, m	Stroke/ bore	Speed, rev/min	bmep, atm	Power per unit volume kW/dm³	Weight/ power ratio, kg/kW	Approx. best bsfc, g/kW·h
Spark-ignition engines:									
Small (e.g., motorcycles)	2S,4S	6–11	0.05–0.085	1.2–0.9	4500–7500	4–10	20–60	5.5–2.5	350
Passenger cars	4S	8–10	0.07–0.1	1.1–0.9	4500–6500	7–10	20–50	4–2	270
Trucks	4S	7–9	0.09–0.13	1.2–0.7	3600–5000	6.5–7	25–30	6.5–2.5	300
Large gas engines	2S,4S	8–12	0.22–0.45	1.1–1.4	300–900	6.8–12	3–7	23–35	200
Wankel engines	4S	≈ 9	0.57 dm³ per chamber		6000–8000	9.5–10.5	35–45	1.6–0.9	300
Diesel engines:									
Passenger cars	4S	17–23	0.075–0.1	1.2–0.9	4000–5000	5–7.5	18–22	5–2.5	250
Trucks (NA)	4S	16–22	0.1–0.15	1.3–0.8	2100–4000	6–9	15–22	7–4	210
Trucks (TC)	4S	14–20	0.1–0.15	1.3–0.8	2100–4000	12–18	18–26	7–3.5	200
Locomotive, industrial, marine	4S,2S	12–18	0.15–0.4	1.1–1.3	425–1800	7–23	5–20	6–18	190
Large engines, marine and stationary	2S	10–12	0.4–1	1.2–3	110–400	9–17	2–8	12–50	180

Figure 16: Typical Design and operating data for internal combustion engines

2.4 Exhaust Gas Emissions

The combustion of hydrocarbon fuel consumes O2 from the atmosphere and releases equivalent amount of H2O and CO2 as a primary output and always with the addition other compounds including hydrocarbons (CH4, C2H2, C2H6,C2H8, C6H6, CH2, CHO, etc..), carbon monoxide (CO), nitrogen oxides (NO, N2O) and reduced nitrogen (NH3 and HCN), sulphur gases (SO2, OCS, CS2), halo- carbons (CHCI and CH3Br), and particles.

Pollutant	Description	Primary Sources	Effects
Carbon Monoxide CO	CO is odorless, colorless, poisonous gas. It is produced by the incomplete combustion of fossil fuels.	Sources of CO are cars, trucks, buses, small engines and some industrial processes.	CO interferes with the blood's ability to carry oxygen, slowing reflexes and causing frowziness. In high concentration, CO can also cause death.
Nitrogen Oxides NOx	When combustion temperature exceed 538°, nitrogen and oxygen combine to form nitrogen oxides.	NOx comes from burning fuels in vehicles, power plants and industrial boilers.	NOx can make the body vulnerable to respiratory infections, lung diseases and cancer. They contribute to the brownish haze seen over cities and to acid precipitation.
Sulfur Dioxide SO2	SO2 is produced by chemical interactions between sulfur and oxygen. It is colorless with pungent odor.	SO2 comes mostly from burning fuels containing sulfur, melting of sulfur-hearing metals and certain industrial processes.	SO2 contribute to acid precipitation and sulfuric acid. Secondary pollutants that result from reactions with SO2 can harm plant life and irritate the respiratory systems of humans.
Volatile Organic Compounds VOCs and HC	VOCs are organic chemicals that vaporize readily and form toxic fumes.	VOC's come from burning fuels. HC are mainly due to their incomplete combustion.	VOCs contribute to smog formation and can cause serious health problems, such as cancer. They may also harm plants.
Particulate Matter PM	Particulate are tiny particles or liquid or solid matter, such as dust, soot, metals and various chemicals.	Most particulate come from construction, agriculture, forestry and fires. Vehicles and industrial processes also have a contribution.	Particulates can form clouds that reduce visibility and cause a variety of respiratory problems. Particulate have also been linked to cancer. They may also corrode metals and erode buildings and sculptures.

Figure 17: Primary Industrial Air Pollutants

Pollution can be defined as “the introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological system, damage to structures or amenity, or interference with legitimate uses of the environment”.

All the substances that are visible to the eye or under a microscope (dust, pollen, etc.) and those substances that are not (sulphur dioxide, ozone, etc.) affect directly air quality. Air pollutants in the atmosphere cause concern primarily because of their potential negative consequences on human health, they can be either gaseous or particulate in form.

Common gaseous pollutants are carbon monoxide, sulphur dioxide, nitrogen oxides, and ozone. Particulate matter can be made up of many different compounds including mineral, metallic, and organic compounds, and can be further differentiated by size (particles, aerosols, and fine particles).

Another important distinction is the difference between primary and secondary air pollutants.

Primary pollutants are directly emitted to the atmosphere, like carbon monoxide emitted from trucks and automobiles, and sulphur dioxide and nitrogen oxides emitted from factory and power plant smoke-stacks.

Secondary pollutants are the result of chemical reactions with other elements in the atmosphere. One of the pollutants of most concern in urban areas is ozone, that is a secondary pollutant formed from the photochemical reaction of volatile organic compounds and nitrogen oxides.

Not all air pollutants have the same effects on human health, and there are some that are particularly dangerous while others are more bearable in equivalent quantities. The following figure shows a classification of pollutants according to their degree of dangerousness.

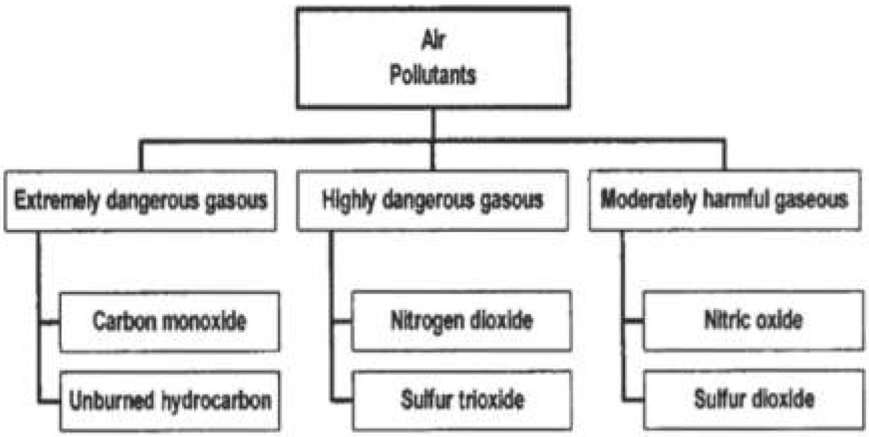


Figure 18: Air Pollutants macro-classification

2.5 Atmospheric Pollution.

Nowadays pollution has become one very discussed and important topic, since is widespreadly known that it has increased drastically in the last decade, affecting our daily life in a negative way. The main sources of pollution are though, still unknown to many, that allocates the causes of it to the wrong factors.

The term “smog” was first introduced in 1911, in the UK during the first industrial revolution, identifying the simultaneous presence of smoke and fog. The combustion of coal, with high sulphur content, caused the formation of smog where high levels of fog were present: the natural fog became rich in sulphur, released from coal combustion.

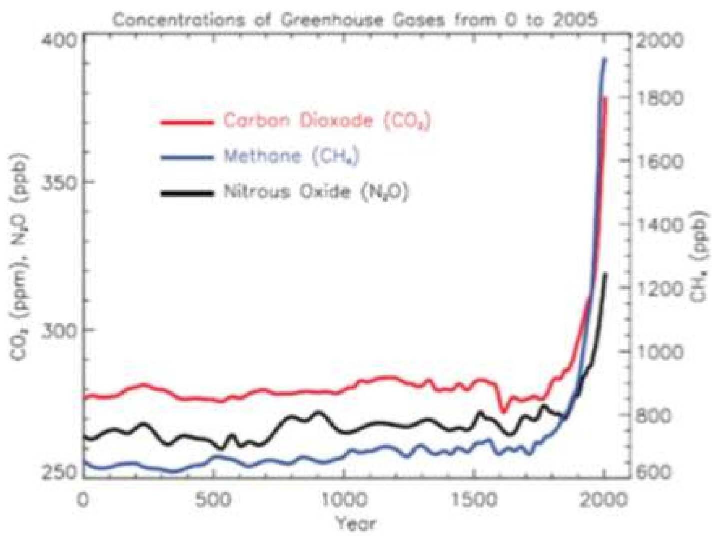


Figure 19: Concentration of Greenhouse Gases from 0 to 2005

With the same term it is usually referred also to the pollution determined by Ozone. This process is different and takes place in different geographical regions.

Bio-geochemist Haagen-Smith, from California, was the first to formulate the idea of the formation of urban ozone, or L.A smog, due to the reaction of sunlight on reactive hydrocarbons and nitrogen oxides produced by oil refineries and automobiles. The produced ozone affected human beings by means of reduction of lungs functionality and respiratory symptoms.

Later on, deeper studies identified two main processes: A constant decline of about 4% per decade of ozone in Earth's stratosphere and a way larger decrease over the polar regions. This particular process is better known as Ozone Hole.

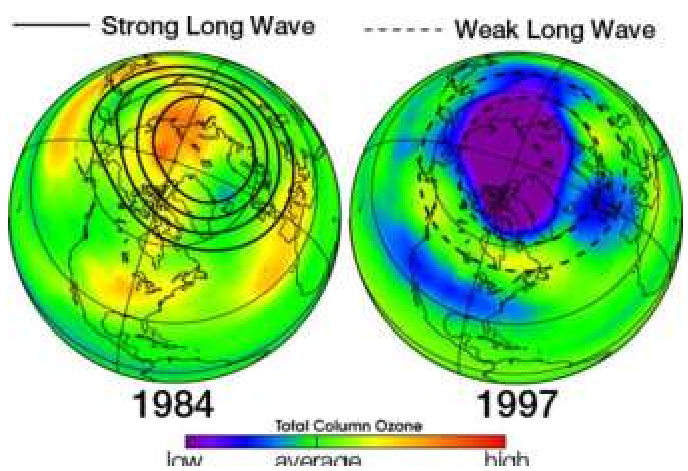


Figure 20: Ozone Hole Evolution 1984-1997

About halfway through the stratosphere, at 25-30 km, there is a band of a substance called Ozone. This band is called Ozonosfera. It is thicker at the equator, where ultraviolet radiation is more intense, and more thin at the poles.

Ozone is a substance consisting of 3 oxygen atoms (O3), present in the stratosphere, which "filters" the ultraviolet rays through a continuous recombination: the oxygen molecule (O2) present in the stratosphere, absorbing the energy of ultraviolet rays decomposes into 2 oxygen atoms, which then attack to another molecule of O2 forming ozone (O3), which is then decomposed again, always by ultraviolet rays, in an atom and a molecule of oxygen, which recombine overnight.

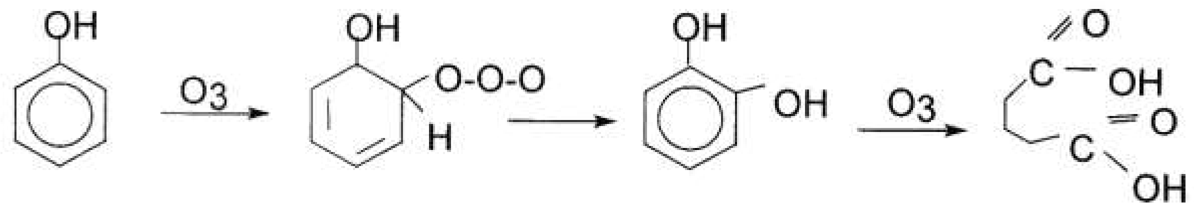


Figure 21: Ozone Decomposition and Recombination

This cycle continues to infinity and therefore the absorption of the rays ultraviolet is constant. However, there are substances called Chlorofluorocarbons (CFC), that, at high altitude, because of the ultraviolet rays, break down. This process is called "Breakdown". The substances produced by breakdown (especially chlorine) bind with oxygen and prevent the formation of ozone.

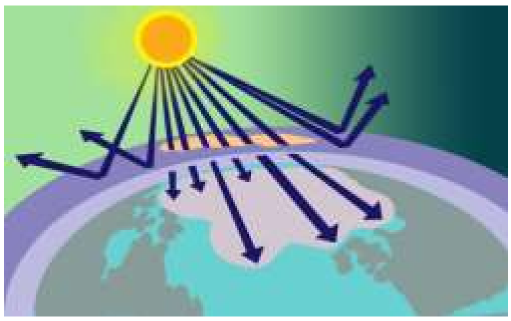


Figure 22. Rays Penetration

The main consequence is that the planet is less protected by solar radiations at high frequency, that can reach the surface of the Earth. Because the Earth's surface is colder than the Sun, it radiates at wavelengths that are much longer than the wavelengths that were absorbed (Figure 23). Most of this thermal radiation is absorbed by the atmosphere and warms it. The atmosphere also gains heat by sensible and latent heat fluxes from the surface. The atmosphere radiates energy both upwards and downwards; the part radiated downwards is absorbed by the surface of Earth. This leads to a higher equilibrium temperature than if the atmosphere were absent.

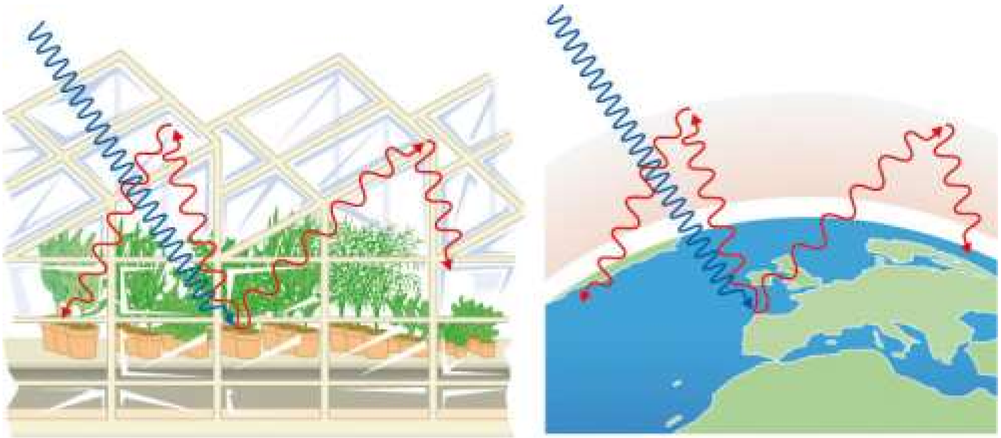


Figure 23: Greenhouse Effect

This process is strictly linked to another big environmental issue: The Green House effect.

The greenhouse effect is a natural feature of all the planets with an atmosphere, which serves to trap the infrared rays produced by the sun inside the atmosphere and to shield some dangerous radiation, so as not to have excessive temperature changes, as happens for example on the Moon, which has no atmosphere (temperatures go from -230 ° C at night to + 120 ° C during the day).

The gases that trap the sun's rays are the anhydride carbon dioxide (CO_2), water vapour and methane (CH_4). So the greenhouse effect allows life on Earth, but only if the gases they are present in the right quantity.

In recent years the increase of carbon dioxide in the air has, obviously, led to the increase of the greenhouse effect.

Temperatures have drastically increased over the last years as shown by the following figures, according to the three major compilations based on measured surface temperatures: GISS, HadCRU and NCDC.

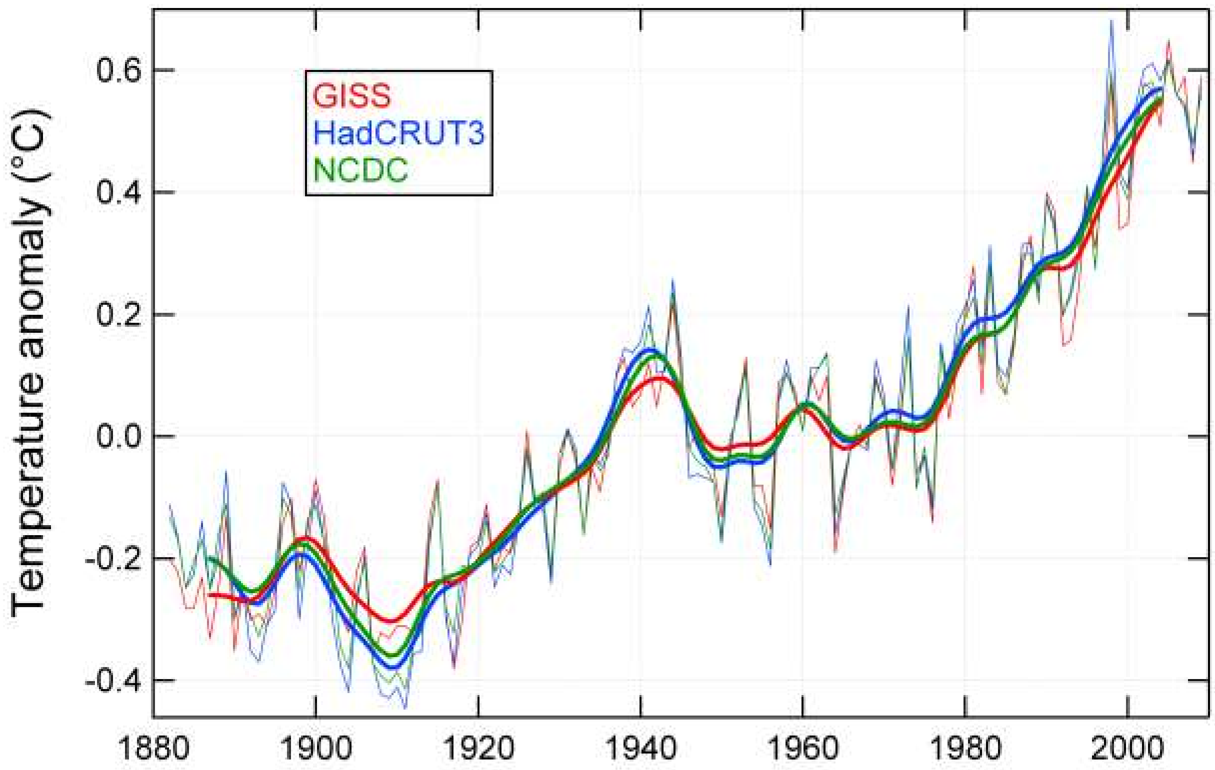


Figure 24: Temperature Anomaly Evolution 1880- 2015

Temperature anomaly is the difference between the long-term average temperature (sometimes called a reference value) and the temperature that is actually occurring. In other words, the long-term average temperature is one that would be expected; the anomaly is the difference between what you would expect and what is happening.

A positive anomaly means that the temperature was warmer than normal; a negative anomaly indicates that the temperature was cooler than normal.

It is more useful to use temperature anomalies and not the actual temperature measurements cause actual temperature measurements are often difficult to gather. Some areas in the world have few temperature measurement stations (for example, remote jungles and deserts), and temperatures must be estimated over large regions.

Those are just two of the main reasons why over the last decades people have become particularly concerned with topics as pollutions and global warning. From the institutional point of view, it translated into regulations and limitations, that affected strongly the development of automotive industry.

Nowadays human activities result in emissions of four principal greenhouse gases: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and the halocarbons (a group of gases containing fluorine, chlorine and bromine).

These gases accumulate in the atmosphere, causing concentrations to increase with time. Significant increases in all of these gases have occurred in the industrial era and are all attributable to human activities.

Cars and Transportation in general accounts for about 20% of air pollution, even if they are always regarded as one of the most affecting cause.

Most of it is still due to the energy generation, even if the future trend is always more towards an environmentally friendly way of generating power. The actual demand of energy is anyway huge, and to properly provide all the people with the needed amount, the use of old-style factories is still in place.

In the same way are all the factories consuming huge amount of power and using a lot of materials and transforming them in processes whose final results affect directly air and water. It is not negligible also the pollutions due to everyday life, from all the small things that we have in our houses like domestic appliances (mainly coolers and fridges).

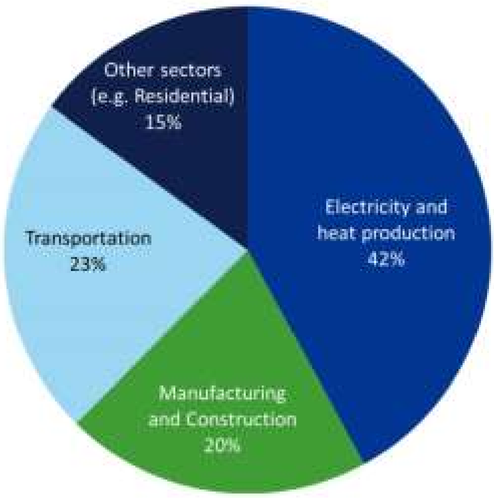


Figure 25: Total Emissions sources in the USA (2014)

Source: International Energy Agency

3.POLLUTANT FORMATION IN THE INTERNAL COMBUSTION ENGINE

Figure 26: Intensive Smog in Urban Area

Let us now analyze the formation of pollutant inside an engine.

The ideal, complete combustion of pure fuel gives the following primary combustion products: H2O, CO2, N2 but the absence of ideal condition for combustion combines with the composition of the fuel itself to produce a certain number of toxic components in addition to the primary combustion products.

The spark-ignition engine exhaust gases are formed also by:

- oxides of nitrogen (nitric oxide, NO, and small amounts of nitrogen dioxide, NO2 collectively known as NOX).
- carbon monoxide (CO).
- organic compounds which are unburned or partially burned hydrocarbons (HC).

According to the engine design and operating conditions the relative amounts are variable but are of the order of:

- NOx 500 to 1000 ppm or 20 g/kg fuel.
- CO, 1 to 2 percent or 200 g/kg fuel.
- HC, 3000 ppm (as C1) or 25 g/kg fuel.

Additional emissions are formed by the stem from the engine's crankcase ventilation system and the combustion gases that travel along the cylinder walls and into the crankcase, whence they are returned to the intake manifold for renewed combustion within the engine.

Diesels generate only negligible amounts of these bypass emissions: only about 10% as much pollution as the bypass gases in a gasoline engine. They can escape from vehicles powered by gasoline engines when volatile components in the fuel evaporate and emerge from the fuel tank, regardless of whether the vehicle is moving or parked.

Evaporative emissions from diesels are not of major concern, as diesel fuel possesses virtually no highly volatile components.

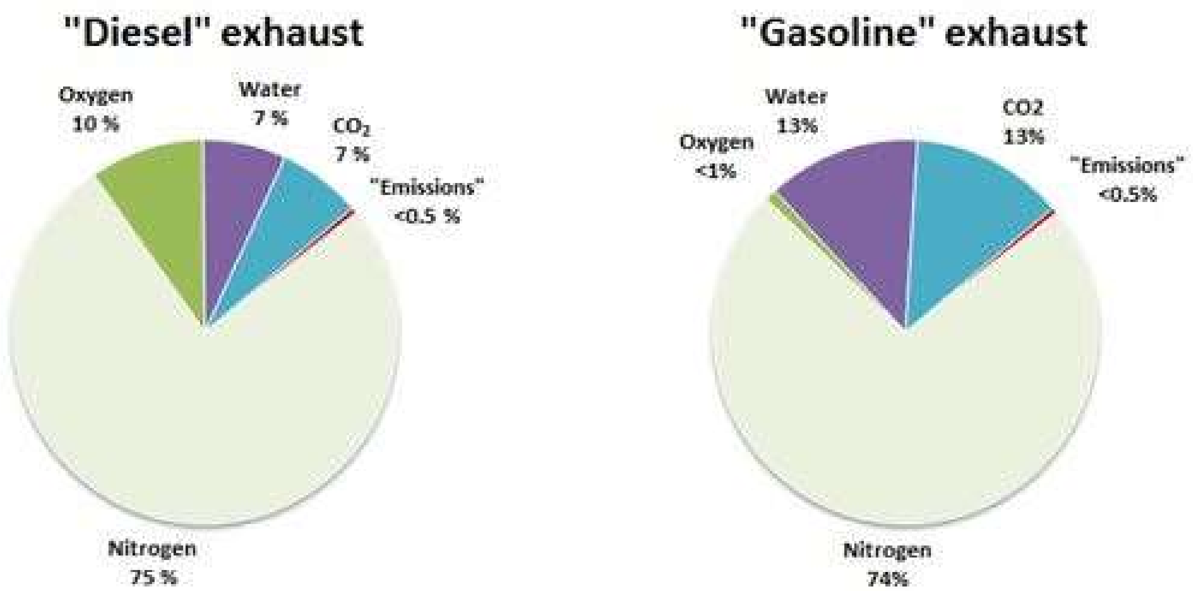


Figure 27: Composition of exhaust gas from gasoline and diesel engines in percentage

3.1 Carbon dioxide (C02)

In complete combustion, the hydrocarbons in the fuel's chemical bonds are transformed into carbon dioxide (CO2), which makes up approximately 13.7% of the exhaust gases. The amount of converted carbon dioxide in the exhaust is a direct index of fuel consumption. Thus the only way to reduce carbon-dioxide emissions is to reduce fuel consumption.

Carbon dioxide is a natural component of atmospheric air, and the CO2 contained in automotive exhaust is not classified as a pollutant. However, it is one of the substances responsible for the greenhouse effect and the global climate change that this causes.

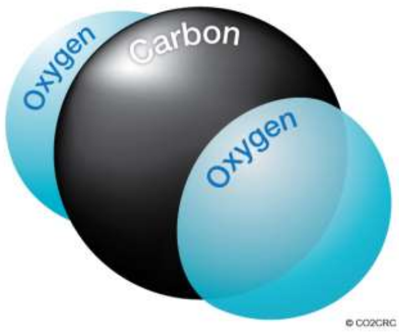


Figure 28: CO2 molecular composition

Because of that, C02 emissions have become a big concern for the official institution, that are using this number as one of the main parameter to control and limit the sales of new cars, as we will see further on.

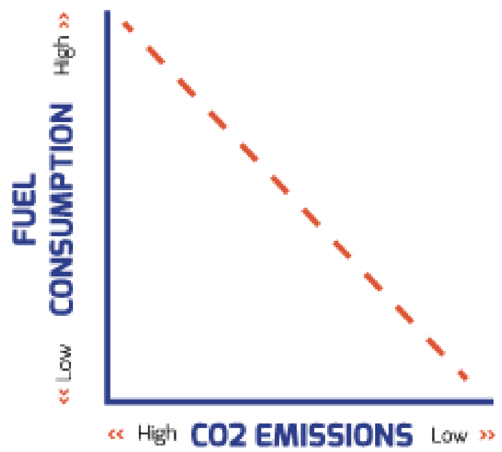


Figure 29: Relation between CO2 Emissions and Fuel Consumption

Due to the chemical composition of fuels, gasoline is the solution that on average, in the same conditions, emits a fewer quantity of CO2 per litre, as shown in the following table. In real life use anyway, as written before, Diesel engines are capable of a real higher efficiency, and so of a total emission of CO2 smaller than an equivalent gasoline engine, due to a better fuel consumption.

CO_2 produced per unit volume and mass of fuel			
Fuel type	Density (kg/l)	CO_2 (kg/l of fuel)	CO_2 (kg/kg of fuel)
Gasoline	0.750	2.33	3.10
Diesel fuel	0.835	2.64	3.16
Equivalence between fuel consumption and CO_2			
Gasoline	1 l/100 km emits 23.3 g/km of CO_2		
Diesel fuel	1 l/100 km emits 26.4 g/km of CO_2		

Table 2 CO2 produced per unit volume per mass of fuel

As stated before, nowadays diesel engines can produce more power and torque with lower CO2 rates when compared to equivalent petrol engines. On average the power output of Diesel engines registered in H1 2017 in the EU is 142 HP and 115 g/km of CO2. At the same time the average output of petrol engines is 123 HP with 122 g/km of CO2.

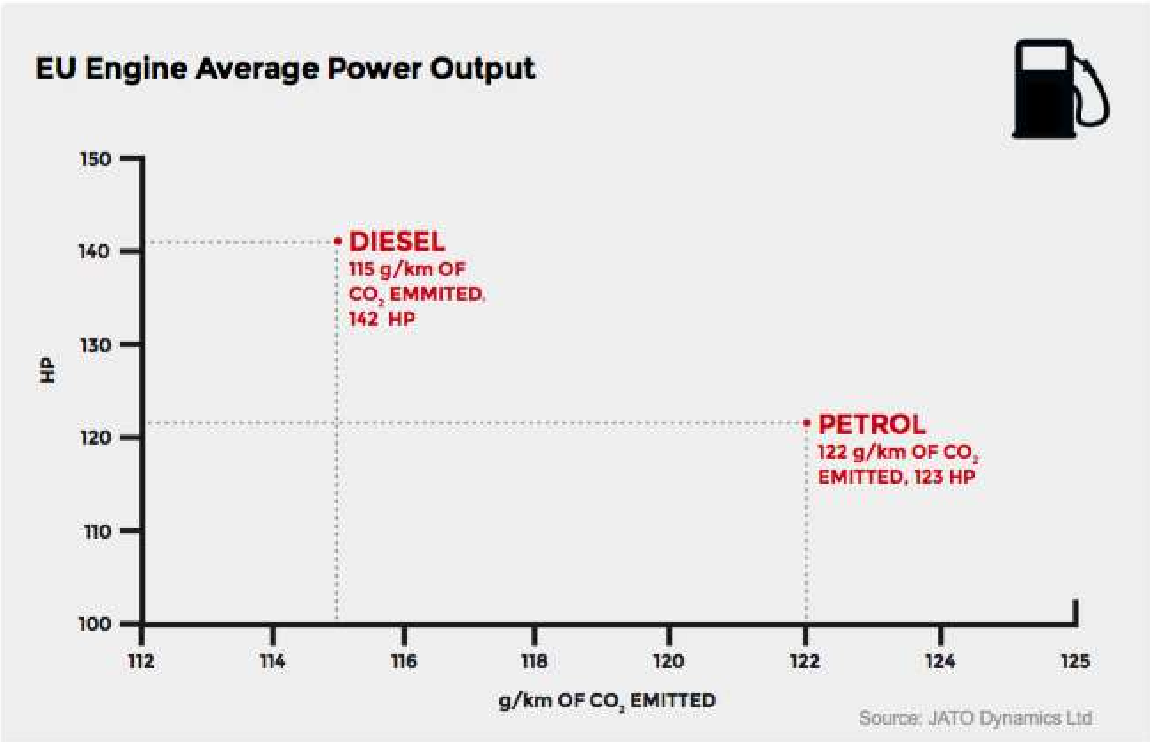


Figure 28: EU Engine Average Power Output

3.2 Carbon monoxide (CO)

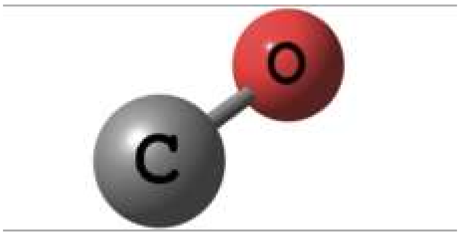


Figure 29. CO Molecular Composition

Carbon monoxide is a colourless, odourless and tasteless but poisonous gas that results from incomplete combustion in rich air/fuel mixtures under conditions characterized by an air deficiency. Carbon monoxide is also produced during operation with excess air, but the concentrations are minimal, and stem from brief periods of rich operation or inconsistencies within the air/fuel mixture. It is formed also by means of fuel droplets that fail to vaporize form pockets of rich mixture that do not undergo a complete combustion.

In case of rich fuel-air mixtures, there is insufficient oxygen to burn fully all the carbon in the fuel to CO2; also, in the high-temperature products, even with lean mixtures, dissociation ensures that there are significant CO levels. Later, in the expansion stroke, the CO oxidation process also freezes as the burned gas temperature falls.

CO enters the blood stream and reduces oxygen delivery to the organs and tissues. People with heart disease are particularly sensitive. Exposure to high levels is linked with impairment of vision, work capacity, learning ability and performance of difficult tasks. Unborn or new-born children and people with heart disease are in greatest danger from this pollutant, but even healthy people can experience headaches, fatigue and reduced reflexes due to CO exposure.

Most of CO Emissions are due to transportation's field, split half and half between road and other means.

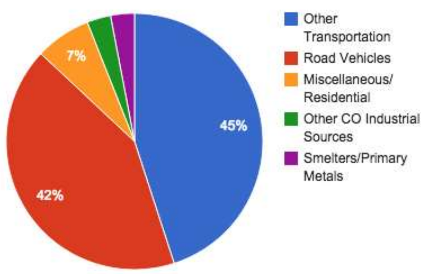


Figure 30: Main Sources of CO Emissions

In the engine, the high process temperatures that accompany high torque foster secondary reactions in CO during the ignition stroke: CO oxidizes to form CO2.

Within the rich range, CO emissions display a virtually linear correlation with the excess-air factor, as a result of the incomplete carbon oxidation during operation with an air deficiency.

In the lean range (air surplus) CO emissions remain at extremely low levels, and the influence of changes in the excess-air factor is minimal. Under these conditions the only source of CO generation is inefficient combustion stemming from inconsistencies in the air/fuel mixture.

3.3 Hydrocarbons (HC)

Unburned Hydrocarbons, or HC, is the generic term for the entire range of chemical compounds formed by hydrogen H with carbons atoms C.

HC emissions are due to the oxygen deficiency to support complete combustion of the air/fuel mixture. The combustion process also produces new hydrocarbon compounds not initially present in the original fuel by separating extended molecular chains. Aliphatic hydrocarbons (alkanes, alkenes, alkines and their cyclical derivatives) are virtually odourless. Cyclic aromatic hydrocarbons such as benzol, toluol and polycyclic hydrocarbons emit a discernible odour.

Aspiration pneumonitis is the most common complication of hydrocarbon exposure, followed by central nervous system (CNS) and cardiovascular complications, as well as problems linked to eye, nose and throat irritations. A chronic exposure is also studied along as one of the mains causes of cancer.

The unburned hydrocarbon (HC) emissions have several different sources:

The increasing cylinder pressure during compression and combustion, pushes some of the gases in the cylinder into crevices, or narrow volumes, connected to the combustion chamber: the volumes between the piston rings, and cylinder wall are the largest of these. Most of this gas is unburned fuel-air mixture that escapes the primary combustion process because the entrance to these crevices is too narrow for the flame to enter. This gas leaving these crevices later in the expansion and exhaust processes, is one source of unburned hydrocarbon emissions.

Another possible source is the combustion chamber walls. A quench layer containing unburned and partially burned fuel-air mixture is left at the wall when the flame is extinguished as it approaches the wall. While it has been shown that the unburned HC in these thin (≤ 0.1 mm) layers burn up rapidly when the combustion chamber walls are clean, it has also been shown that the porous deposits on the walls of engines in actual operation do increase engine HC emissions.

A third source of unburned hydrocarbons is believed to be any engine oil left in a thin film on the cylinder wall piston and perhaps on the cylinder head. These oil layers can absorb and desorb fuel hydrocarbon components, before and after combustion, respectively, thus permitting a fraction of the fuel to escape the primary combustion process unburned.

Another source of HC in engines is incomplete combustion due to bulk quenching of the flame in that fraction of the engine cycles where combustion is especially slow. Such conditions are most likely to occur during transient engine operation when the air fuel ratio, spark timing, and the fraction of the exhaust recycled for emission control may not be properly matched.

Temperatures within the combustion chamber rise as torque generation increases. As a result, the depth of the zone next to the cylinder walls in which the flame is extinguished shrinks as torque rises. This reduces the extent of the low-temperature zone where unburned hydrocarbons could be produced.

The high exhaust-gas temperatures that accompany higher combustion chamber temperatures under high-torque operation promote secondary reactions in the unburned hydrocarbons during the ignition and exhaust strokes. Because high-torque operation equates with higher temperatures in combustion chambers and exhaust gases, it leads to reductions in quantities of unburned hydrocarbons relative to units of power generated.

By reducing the time available for forming and then combusting the mixture, higher engine speeds lead to higher gasoline-engine HC emissions. During operation with excess fuel (air deficiency), incomplete combustion leads to generation of unburned hydrocarbons. Richer mixtures produce progressively greater HC concentrations.

This is why richer mixtures (with progressively lower excess-air factor λ) are characterized by increased HC emissions throughout the rich-mixture range ($\lambda < 1$).

3.4 Nitrous oxides (NOx)

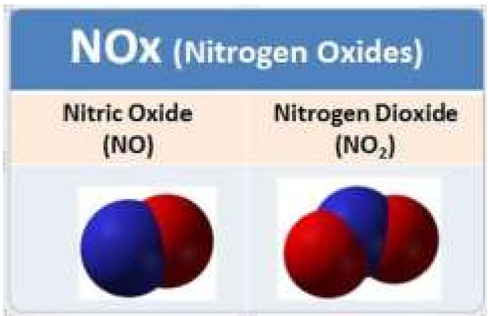


Figure 31: NOx Molecular Composition

Nitrous oxides, or oxides of nitrogen, is a generic term representing chemical compounds based on nitrogen and oxygen, as a result from secondary reactions that occur in all combustion processes where air containing nitrogen is burned.

The primary forms encountered in the exhaust gases from internal-combustion engines are nitrogen oxide (NO) and nitrogen dioxide (NO2), with dinitrogen monoxide (N20) also present in minute concentrations.

Nitric oxide (N0) forms throughout the high-temperature burned gases behind the flame through chemical reactions involving nitrogen and oxygen atoms and molecules, which do not attain chemical equilibrium.

The higher the burned gas temperature, the higher the rate of formation of NO.

As the burned gases cool during the expansion stroke the reactions involving NO freeze, and leave NO concentrations far in excess of levels corresponding to equilibrium at exhaust conditions.

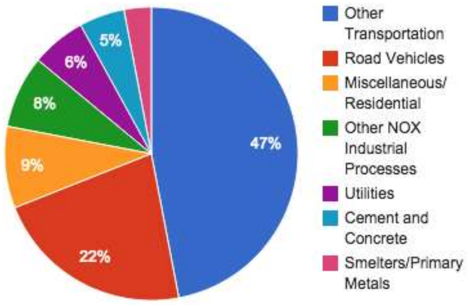


Figure 32: Main Sources Of NOx Emissions

3.4.1 Ozone and smog

As a consequence of the exposure to the sun's radiation, nitrogen-dioxide molecules (NO2 slipt producing:

$$NO_2 \rightarrow NO + O \quad \text{(nitrogen oxide and atomic oxygen)}$$
$$O + O_2 \rightarrow O_3 \quad \text{(ozone)}$$

There are no evidences of direct contact or mutual movement between the ozone formed in this way at ground level and the stratospheric ozone that reduces the amount of ultraviolet radiation penetrating the earth's atmosphere. This is mainly affected by CFC gases, as stated in Paragraph 2.5.

Ozone formation is also promoted by volatile organic compounds. This is why higher ozone levels are registered during summer days with high temperature and few air circulation, when high levels of air pollution are present. It is not limited to the summer, it can also occur in winter in response to atmospheric layer inversions and low wind speeds. The temperature inversion in the air layers prevents the heavier, colder air containing the higher pollutant concentrations from rising and dispersing.

A physical consequences of the exposure to ozone is the irritation of the mucous membranes, eyes and respiratory system. It can also reduce visibility, that' s the origin of the term smog, which combines "smoke" and "fog".

3.4.2 Kinetics of Nitrogen Compounds

The global emission of NOx and N2O to the atmosphere is significant, and the understanding of the NOx emission and its reduction technologies, necessitates the understanding of the reaction mechanism for formation and removal of the various nitrogen oxides.

Four mechanisms have been identified for forming nitrogen oxides in combustion processes:

- thermal-NO
- prompt-NO
- fuel-NO
- nitrous oxide N2O

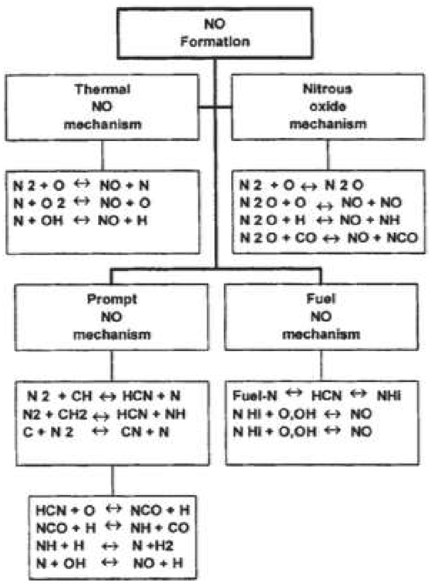


Figure 33: Nitric Oxide Mechanisms

NO

It forms in the flame front and the post flame gases. The flame reaction zone inside the engine is extremely thin (~0.1 mm) since combustion occurs at high pressure and the time within this zone is short. Furthermore, the cylinder pressure rises during most of the combustion process, so the burned gases produced early in the combustion process are compressed to a higher temperature than they reached immediately after combustion. Thus, NO formation in the post flame gases almost always dominates any flame-front-produced NO. The combustion and NO formation processes are decoupled and the concentrations of O, O2, OH, H, and N2 are approximated by their equilibrium values at the local pressure and equilibrium temperature.

NO2

For burned gases at typical flame temperatures, NO2 and NO ratios should be negligibly small. While experimental data show this is true for spark-ignition engines, in diesels NO2 can be 10 to 30 percent of the total exhaust oxides of nitrogen emissions.

Figure 34 shows examples of NO and NO2 emissions data from a spark ignition and a diesel engine. The maximum value for the ratio (NO2/NO) for the SI engine is 2 percent, at an equivalence ratio of about 0.85. For the diesel this ratio is higher, and is highest at light load and depends on engine speed.

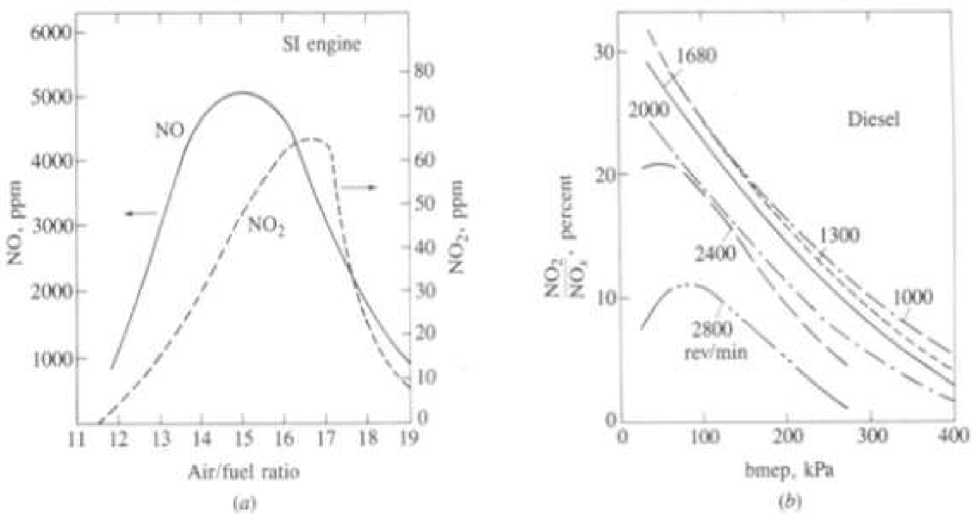


Figure 34: a) NO and NO2 concentration in SI engine exhaust as a function of air/fuel ratio b) NO2 as percent of total NOx in diesel exhaust as function of load and speed

3.4.3 Raw NOx emissions

As a influence of torque, the higher combustion chamber temperatures that accompany increased torque generation promote the formation of NOx. As torque output rises, raw NOx emissions display a disproportionate increase.

NOx emissions decrease drastically with increasing rpm because there is less reaction time available for the formation of NOx at high engine speeds.

The residual gases in the combustion chamber lead to lower peak temperatures. Because levels of residual gases tend to fall off as engine speed rises, the effect counteracts the response pattern described above.

Within the rich range ($\lambda < 1$) NOx emissions increase as a consequence of the increases in the excess-air factor by rising. This is caused by the progressively higher oxygen concentrations in the exhaust gas, which inhibit reduction of the nitrous oxides. Within the lean range ($\lambda > 1$) emissions of NOx respond to higher excess-air factors by falling as the decreasing density of the air/fuel mixture leads to progressively lower combustion-chamber temperatures. The highest value of NOx emissions are registered with slightly lean mixtures in the range of λ=1.05...1.1.

3.5 Sulphur dioxide (SO2)

Sulphurous compounds in exhaust gases, primarily sulphur dioxide, are a consequence of the sulphates contained in fuels. A relatively small proportion of these pollutant emissions derives from motor vehicles.

Sulphur dioxide is emitted when fuel containing sulphur is burned in diesel engines. Sulphur dioxide exposure constricts air passages, creating problems for people with asthma and for young children, whose small lungs need to work harder than adults' lungs.

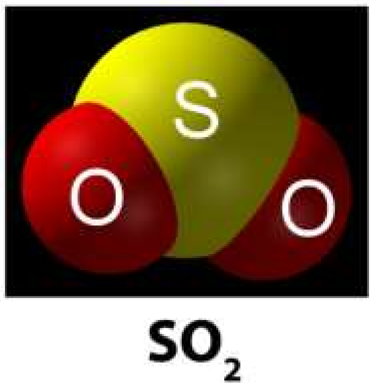


Figure 35: SO2 Molecular Composition

These emissions are not restricted by official emissions limits, but starting from the 1990s, with subsequent directives, the sulphur content was gradually reduced to reach the same level both in gasoline and in diesel fuel. The earlier limits on sulphur concentrations within fuel of 500 ppm (parts per million, 1000 ppm = 0.1 %), valid until the end of 1999, have now been tightened by EU legislation. The limits valid from 2000 onward, have been 150 ppm for gasoline and 350 ppm for diesel fuels, it was later reduced from 500 to 350, to 150, to 50 and finally to 10 ppm.

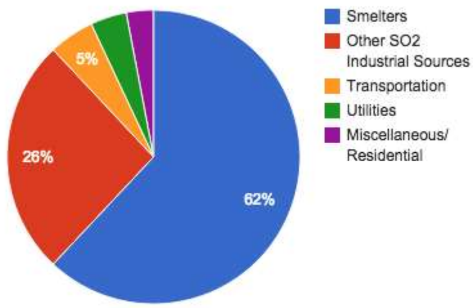


Figure 36: Sources of SO2 Emissions

3.6 Particulates

Particulates is a direct consequence of the incomplete combustion. Exhaust composition varies as a function of combustion process and engine operating condition; particulates basically consist of hydrocarbon chains (soot) with an extremely extended specific surface ratio.

Unburned and partially combusted hydrocarbons form deposits on the soot, where they mix with aldehydes, with their strong odour. Aerosol components, minutely dispersed solids or fluids in gases, and sulphates bond to the soot. The sulphates result from the sulphur content of the fuel.

Particulate matter includes microscopic particles and tiny droplets of liquid. Because of their small size, these particles are not stopped in the nose and upper lungs by the body's natural defences but go deep into the lungs, where they may become trapped and cause irritation. Metabolic processes have some difficulties in removing these undesired components. Exposure to particulate matter can cause wheezing and similar symptoms in people with asthma or sensitive airways. Particulate matter can serve as a vector for toxic air pollutants (see below).

According to the size of the particles is possible to classify them in 3 categories:

- Fine Particles (PM 2.5): Diameter below 2.5 μm; they can enter into the upper respiratory system.
- Ultra-fine particles: Diameter below 0,1 μm; they can enter into the primary bronchi.
- Nanoparticles: Diameter below 0,05 μm; they can enter into the bronchioles and alveoli.

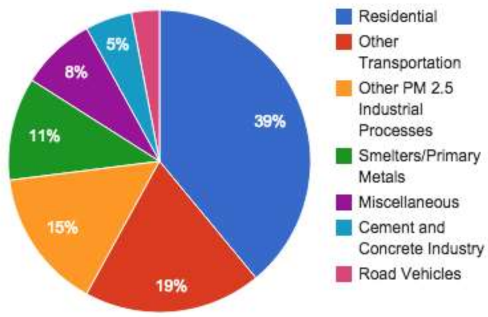


Figure 37: Sources of Particulate

The problem of particulate emissions is primarily associated with diesel engines since the levels of particulate emissions from gasoline engines are almost negligible.

Diesel particulates consist principally of combustion generated carbonaceous material, or soot, on which some organic compounds have been absorbed. The majority of particulate material results from incomplete combustion of fuel hydrocarbons, with the additional contribution of the lubricating oil.

The emission rates fall on the range of 0.2 to 0.6 g/km for light-duty diesels in an automobile. In larger direct-injection engines, particulate emission rates are 0.5 to 1.5 g/brake kWh.

The composition of the particulate material is a function of the conditions of the engine exhaust and particulate collection system. At temperatures above 500°C, the individual particles are principally clusters of many small spheres or spherules of carbon (with a small amount of hydrogen) with individual spherule diameters of about 15 to 30 nm. With temperatures below 500°C, the particles become coated with adsorbed and condensed high molecular weight organic compounds which include: unburned hydrocarbons, oxygenated hydrocarbons (ketones, esters, ethers, organic acids), and polynuclear aromatic hydrocarbons.

The condensed material also includes inorganic species as sulphur dioxide, nitrogen dioxide, and sulphuric acid (sulphates).

3.7 Additional Unregulated Pollutant

Additional types of pollutants are present in exhaust gases, even if their concentrations are definitely lower than those of regulated pollutants. The main ones are lead, benzene, Polynuclear

Aromatic Hydrocarbons (PAH) and aldehydes. Their control consists of introducing additional specifications in fuel composition, such as:

Lead. It was formerly present in gasoline as tetraethyl lead and used to increase the Research Octane Number (RON), thus preventing knocking. Similarly to other heavy metals, its detrimental effects on human brain tissues were recognized at the end of the 1980s and therefore its content was progressively cut to almost zero in the EU from 0.15 to 0.013 g/l. Unleaded gasoline, required by three-way catalysts to meet Euro 1 standard , was thus introduced. In 2000 a further reduction to 0.005 g/l took place to improve catalyst durability. This is now the maximum lead content for the gasoline types distributed in the EU: 91, 95 and 98 RON.

Benzene ($C6H6$). It is the simplest of the ring-shaped aromatic hydrocarbons. It shows the best behaviour against detonation thus allowing the octane number to raise. Unfortunately, it is recognized as being carcinogenic and thus new anti-knock hydrocarbons and components have been introduced to partially compensate for the benzene properties, since starting from year 2000 the benzene percentage in gasoline was lowered from 5% to 1%. As a consequence, the average RON in Europe was reduced from the previous 98 to the present-day 95 RON.

Polynuclear Aromatic Hydrocarbons (PAH) are also considered as being carcinogenic; they are due to the transformation of benzene and other aromatic hydrocarbons during the combustion process. Again the most effective measure is to reduce their quantities in fuels and therefore, starting from year 2000, a specific standard states that aromatic hydrocarbons must not exceed 11 % of diesel fuel.

Aldehydes. The possibility to obtain fuels from agriculture is becoming of increasing interest; the most common biofuels being alcohols, either ethylic or methylic. These fuels, despite some advantages, promote aldehydes formation. Their smell, in the exhaust, is typical and is due to a specific molecular bond: CHO. As known, in Brazil, ethylic alcohol is obtained as a by-product of sugar cane cultivation. In the interested countries, a formaldehyde standard has been introduced considering its carcinogenic risks.

3.8 Pollutant formation as a function of air to fuel ratio.

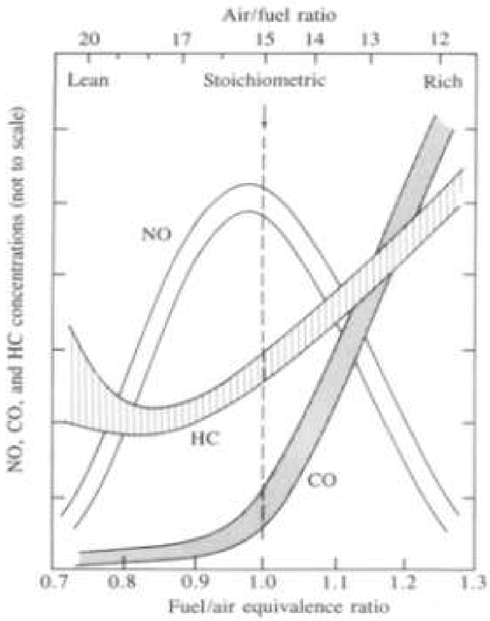


Figure 38: Pollutants Emissions as a function of air to fuel ratio

In order to provide smooth and reliable operation the spark-ignition engine is usually operated close to stoichiometric, or slightly fuel-rich. Figure 38, by Heywood, shows that leaner mixtures are connected with lower emissions until the combustion quality becomes poor, and eventually misfire occurs, when HC emissions rise sharply and engine operation becomes erratic.

In a cold engine, since fuel vaporization is slow, the fuel flow is increased to compensate and obtain an easily combustible fuel-rich mixture in the cylinder. Thus, until the engine warms the mixture is kept rich and, as a consequence, CO and HC emissions are high.

At part-load conditions, lean mixtures which would produce lower HC and CO emissions (at least until the combustion quality deteriorates) and moderate NO emissions could be used. In order to lower the NO levels, recycled exhaust to dilute the engine intake mixture can be used but as a drawback they also deteriorates combustion quality. Exhaust gas recirculation (EGR) is used with stoichiometric mixtures in many engine control systems.

The highest power levels are obtained from the engine with slightly rich-of-stoichiometric mixtures and no recycled exhaust to dilute the incoming charge. Several emission control techniques are required to reduce emissions of all three pollutants, over all engine operating modes, and achieve acceptable average levels.

As inferable from a comparison from Figure 38 and Figure 39, the issue is all about finding the perfect balance between performance and emissions, by regulating the air-to-fuel ratio.

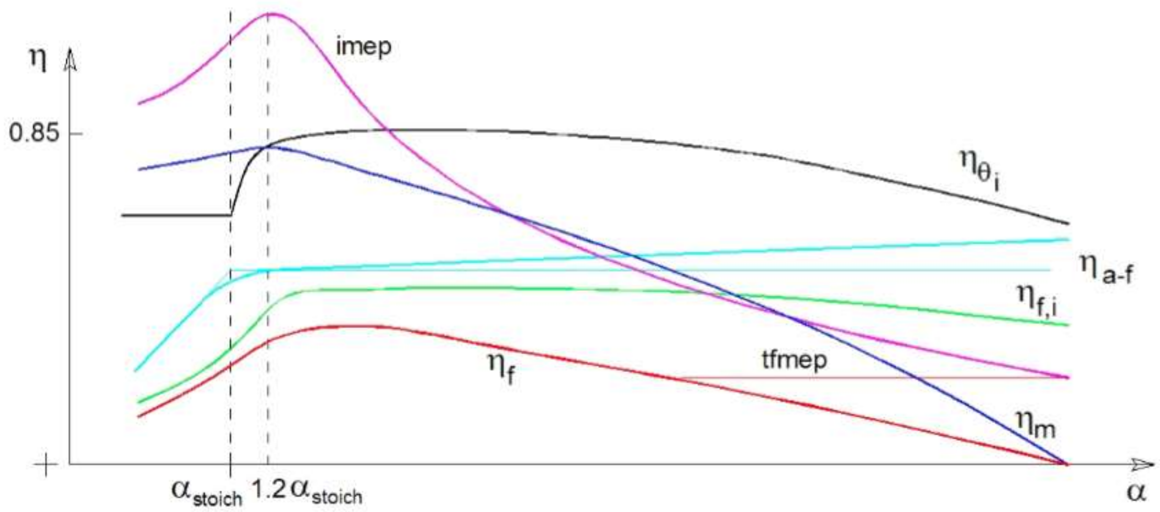


Figure 39: Performances of ICE as a function of air to fuel ratio.

imep = indicated mean effective pressure; tfmep= total friction mean effective pressure; ηf= fuel conversion efficiency; ηm= mechanical efficiency; ηf,i=indicated fuel conversion efificency; ηa-f=air-fiel efficiency; $\eta\vartheta$i= internal thermodynamic efficiency;

In the Diesel engine, combustion is characterized by a non uniform distribution of fuel, since the fuel is injected into the cylinder just before combustion starts. The pollutant formation processes are strongly dependent on the fuel distribution and how that distribution changes with time due to mixing.

Figure 40, by Heywood, illustrates how various parts of the fuel jet and the flame affect the formation of NO, unburned HC, and soot (or particulates) during the “premixed and “mixing-controlled’ phases of diesel combustion in a direct-injection engine with swirl.

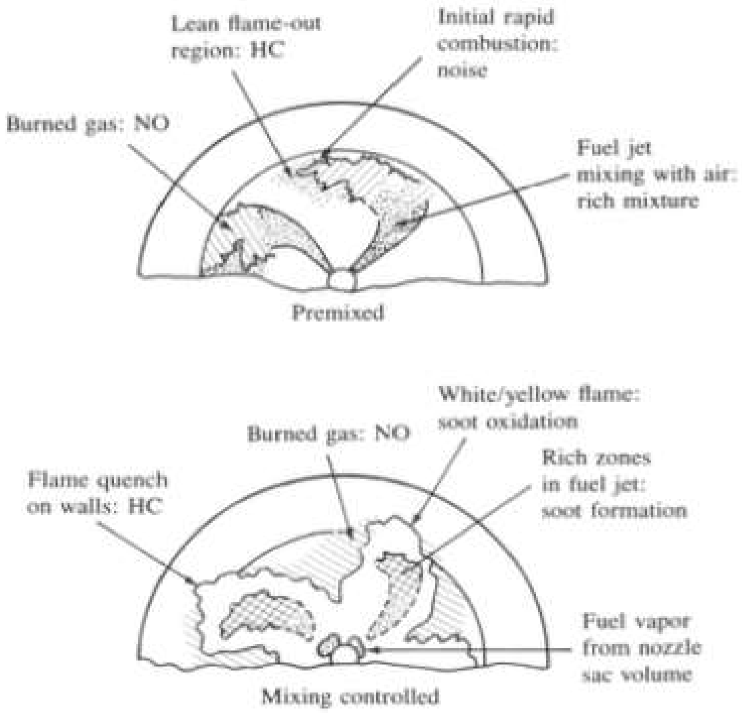


Figure 40: Summary of pollutant formation mechanisms in a direct-injection diesel engine

NO formation takes place in the high-temperature burned gas regions as before, but temperature and fuel air ratio distributions within the burned gases are non uniform and formation rates are highest in the close to-stoichiometric regions.

Soot formation takes place in the rich unburned-fuel-containing core of the fuel sprays, within the flame region, where the fuel vapour is heated because of the mixture with hot burned gases. Soot then oxidizes in the flame zone when it contacts unburned oxygen, giving rise to the yellow luminous character of the flame.

Hydrocarbons and aldehydes originate in regions where the flame quenches both on the walls and where excessive dilution with air prevents the combustion process from either starting or going to completion. Fuel that vaporizes from the nozzle sac volume during the later stages of combustion is also a source of HC. Combustion generated noise is controlled by the early part of the combustion process, the initial rapid heat release immediately following the ignition-delay period.

4.EMISSION REGULATIONS

The first regulations date back to 1970, when the most developed countries as USA, EU and Japan, started to reduce the emissions standards with a future perspective of a level close to zero.

The first EU-wide standard, known as Euro 1, was introduced in 1992. As a consequence, catalytic converters became compulsory on new cars sold as Europe wised up to the need to reduce tailpipe emissions. This effectively standardised fuel injection on new cars.

Since then, we have passed through a series of Euro emissions standards, leading to the current Euro 6, introduced in September 2014 for new type approvals and September 2015 for the majority vehicle sales and registrations.

The regulations, which are designed to become more stringent over time, define acceptable limits for exhaust emissions of new light duty vehicles sold in EU and EEA (European Economic Area) member states.

According to the EU, "the air pollutant emissions from transport are a significant contribution to the overall state of air quality in Europe", with industry and power generation being the other major sources. The aim of Euro emissions standards is to reduce the levels of harmful exhaust emissions, in particular NOx, CO, HC and PM.

The development over time of new technology in order to fit with the new limits has had a positive effect on the quality of exhausted gas emissions, as the SMMT (Society of Motor Manufacturers and Traders in UK) stated:

"It would take 50 new cars today to produce the same amount of pollutant emissions as one vehicle built in the 1970s."

Supported by the following figures:

- Carbon monoxide (CO): petrol down 63%, diesel down 82% since 1993.
- Hydrocarbons (HC): petrol down 50% since 2001.
- Nitrogen oxide (NOx): down 84% since 2001.
- Particulate matter (PM): diesel down 96% since 1993.

Because petrol and diesel engines produce different types of emissions they are subject to different standards. Diesel, for example, produce more particulate matter, or soot, leading to the introduction of diesel particulate filters (DPFs).

The EU has pointed out, however, that NOx emissions from road transport “have not been reduced as much as expected. Since emissions in real-life driving conditions are often higher than those measured during the approval test, in particular for diesel vehicles”.

Over the same time, average new car CO2 emissions have more than halved, going some way to meeting the target average of 95g/km by 2020. CO2 emissions are linked to climate change and subject to different regulations.

4.1 Euro Standards: Chronology

The following table, by the European Commission, shows the dates of introduction of the Euro standards over time. The Euro categories are to be applied to new vehicle models approved after a specific date. Every car sold up to a year after the dates below should conform to the appropriate standards. All the vehicles older than the dates listed below is to be considered Euro 0. Individual vehicles already on sale that were built by, and dispatched from, the manufacturer before 1st June 2015 can continue to be sold until 1st September 2016. This in effect means that a car sold before 1st September 2016 may still have a Euro 5 engine.

Emissions standard	Applied to new passenger car approvals from:	Applied to most new registrations from:
Euro 1	1 July 1992	31 December 1992
Euro 2	1 January 1996	1 January 1997
Euro 3	1 January 2000	1 January 2001
Euro 4	1 January 2005	1 January 2006
Euro 5	1 September 2009	1 January 2011
Euro 6	1 September 2014	1 September 2015

Table 3: Euro standards temporal application

4.2 Euro Emissions Breakdown

The emissions have to be measured following a well-defined driving cycle, able to simulate real driving conditions. In addition to the mentioned limits, gasoline cars must comply with the evaporative emission standard, set to a level of 2 g/test.

4.2.1 Euro 1 (EC93)

Implementation date (new approvals): 1 July 1992.

Implementation date (all new registrations): 31 December 1992.

The first Europe-wide euro emissions standards regulations were introduced in July 1992 and they were not as stringent as they are today.

The main technological solutions adopted were:

- the fitment of catalytic converters became compulsory on all new cars.
- switch to unleaded petrol.

Back then, only hydrocarbons and nitrogen oxide were tested, along with particulate matter in the case of diesel engines. Over the years, the regulations have become stricter and the limits lowered.

PETROL
CO: 2.72g/km
HC + NOx: 0.97g/km

DIESEL
CO: 2.72g/km
HC + NOx: 0.97g/km
PM: 0.14g/km

Table 4: Euro 1 Emissions' limits

4.2.2 Euro 2 (EC96)

Implementation date (new approvals): 1 January 1996.

Implementation date (all new registrations): 1 January 1997.

5 years after Euro 1, the new Euro 2 legislation subsequently reduced the previous limits both for Petrol and Diesel engines.

PETROL
CO: 2.2g/km
HC + NOx: 0.5g/km

DIESEL
CO: 1.0g/km
HC + NOx: 0.7g/km
PM: 0.08g/km

Table 5: Euro 2 Emissions' limits

4.2.3 Euro 3 (EC2000)

Implementation date (new approvals): 1 January 2000.

Implementation date (all new registrations): 1 January 2001.

Euro 3 set a bigger challenge to manufacturers as it split the hydrocarbons and nitrogen oxide limits for petrol and diesel engines, as well as adding a separate nitrogen oxide limit for diesel vehicles. The warm-up period was removed from the test procedure.

PETROL
CO: 2.3g/km
HC: 0.20g/km
NOx: 0.15g/km

DIESEL
CO: 0.66g/km
HC + NOx: 0.56g/km
NOx: 0.50g/km
PM: 0.05g/km

Table 6: Euro 3 Emissions' limits

4.2.4 Euro 4 (EC2005)

Implementation date (new approvals): 1 January 2005.

Implementation date (all new registrations): 1 January 2006.

Although no specific technology is required to meet the requirements, emissions reductions are typically achieved through the use of selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) technologies.

PETROL
CO: 1.0g/km
HC: 0.10g/km
NOx: 0.08g/km

DIESEL
CO: 0.50g/km
HC + NOx: 0.30g/km
NOx: 0.25g/km
PM: 0.025g/km

Table 7: Euro 4 Emissions' limits

4.2.5 Euro 5 (EC2009/9)

Implementation date (new approvals): 1 September 2009.

Implementation date (all new registrations): 1 January 2011.

The big news for Euro 5 was the introduction of particulate filters (DPFs) for all diesel vehicles, along with lower limits across the board. For type approvals from September 2011 and new cars from January 2013, diesel vehicles were subject to a new limit on particulate numbers, thus introducing a further Euro5b standard.

DPFs capture 99% of all particulate matter and are fitted to every new diesel car. Cars meeting Euro 5 standards emit the equivalent of one grain of sand per kilometre driven.

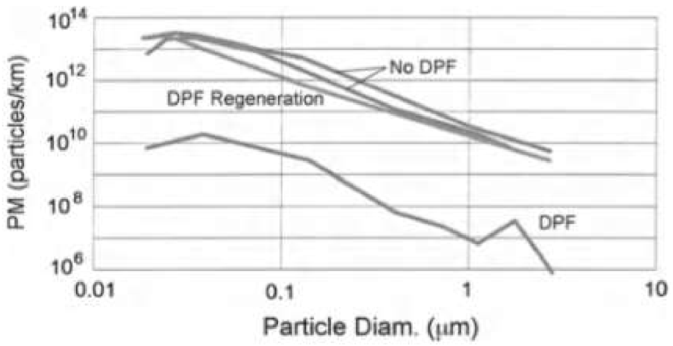


Figure 41: Particle number reduction thanks to DPF

PETROL
CO: 1.0g/km
THC: 0.10g/km
NMHC: 0.068g/km
NOx: 0.06g/km
PM: 0.005g/km (direct injection only)

DIESEL
CO: 0.50g/km
HC + NOx: 0.23g/km
NOx: 0.18g/km
PM: 0.005g/km
PM Euro 5b: 6.0x10 g/km

Table 8: Euro 5 Emissions' limits

Already from 2008, some manufactures introduced on the market cars that could respect those limits, presenting them as Euro5 ready. Those care were anyway registered as Euro4 but with the future prospective of a possible Euro5 re-classification.

- Audi A3 Sportback, A4, A5 e TT
- BMW Series 1
- BMW Series 3 (320d)
- Fiat Bravo 2.0 Multijet
- Peugeot 407 2.0 HDI FAP
- Porsche 911
- Volkswagen Scirocco 1.4 TSI
- Volkswagen Golf VI

4.2.6 Euro 6 (EC2014)

Implementation date (new approvals): 1 September 2014.

Implementation date (all new registrations): 1 September 2015.

The sixth and actual Euro emissions standard was introduced on most new registrations in September 2015. A focus on diesel NOx was the direct result of studies connecting these emissions with respiratory problems. As a consequence, the permitted level of NOx has been slashed from 0.18g/km in Euro 5 to 0.08g/km. This played a major role in the investments to adapt engines to the new standard.

The need arose to support the PN with the PM since some charcoal particles were registered outgoing from petrol engines, smaller than those normally produced by diesel, and consequently, not subject to the limitations applied to the amount of mass per km path.

2011

- Audi (A4, TT, Q7)
- BMW (series 3, series 5, series 7)
- Mercedes-Benz (E, S, R, M, GL)

2012

- Citroen C4 Picasso 2.0 BlueHdi
- Hyundai Santa Fe
- Mazda CX-5 Diesel
- Opel Meriva 1.4 Turbo da 120 CV
- Fiat 500L gasoline

PETROL
CO: 1.0g/km
THC: 0.10g/km
NMHC: 0.068g/km
NOx: 0.06g/km
PM: 0.005g/km (direct injection only)
PN [#/km]: 6.0x10 ^12/km (Euro 6B)
PN [#/km]: 6.0x10 ^11/km (direct injection only)

DIESEL
CO: 0.50g/km
HC + NOx: 0.17g/km
NOx: 0.08g/km
PM: 0.005g/km
PN [#/km]: 6.0x10 ^11/km

Table 9: Euro 6 Emissions' limits

The implementation of the new limits was gradual through different steps.

Euro 6a: Euro 6 emissions requirements excluding the revised measurement procedure for particulates, the particle number standard and the flexible fuel vehicle low temperature emission testing with biofuel 8 (a specific low temperature test for biofuels engines).

Euro 6b: Euro 6 emissions requirements including the revised measurement procedure for particulates, the particle number standard for CI vehicles and the flexible fuel vehicle low temperature emission testing with biofuel.

As a resume, the following graphs show the trend of exhaust gas emission requested by EU over the last years.

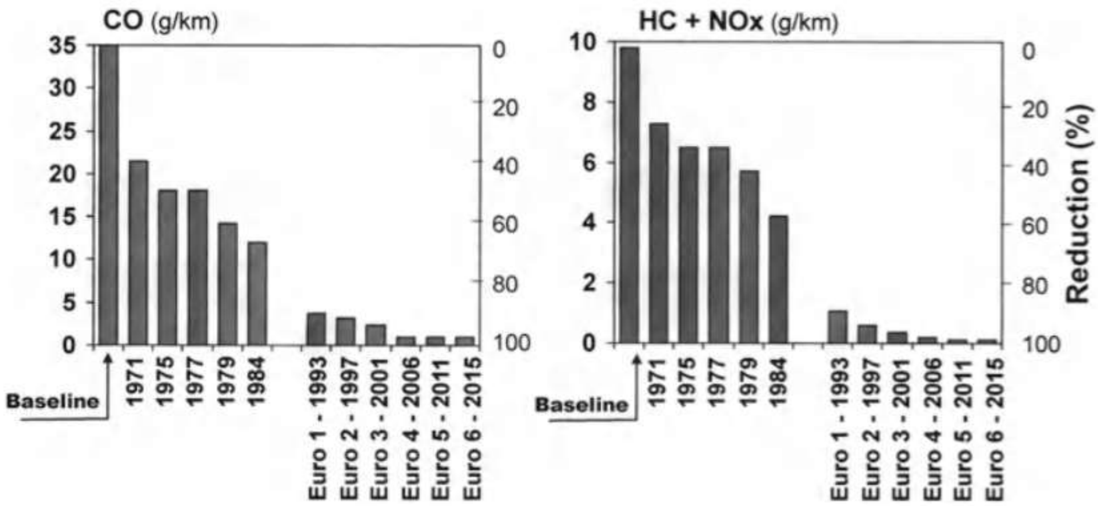


Figure 42. Emission reduction through years for S.I. engine

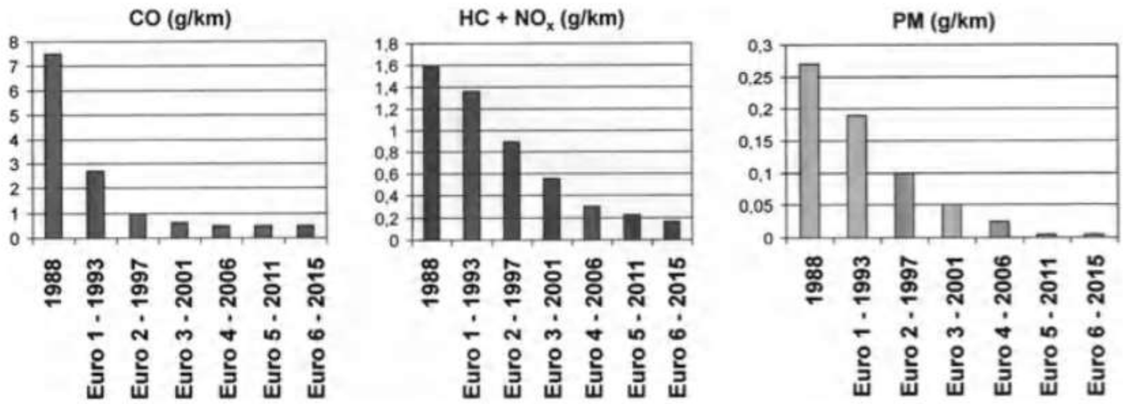


Figure 43: Emission standard sequence through years for Diesel engine.

Source: The Motor Car, Genta, pag. 204,205

4.2.7 Euro 6C

The Euro 6c regulation, which will be mandatory for all the models approved since September 2017 and sold since September 2018, represents the full implementation of Euro 6 Standard. It does not change the previous values for diesel cars (Euro 6a and Euro 6b), but intervenes on petrol engines that will have to reduce the **PN from 6.0x10 ^12/km at 6.0x10 ^11/km**; this is why manufacturers like Peugeot, Mercedes and Volkswagen have already announced new-generation petrol engines equipped with DPF diesel particulate filters.

4.2.7 Euro 6D

The political choices of the EU no longer aim at a pure and simple reduction of exhaust emissions, now also difficult to measure accurately considering the quantities and dimensions of the particles, but to change the homologation cycles closer to those of real use of the car.

Euro6 standard is going to be further developed through a new standard, called Euro6D. It is to be implemented through two different phases: the first, temporary (temp), and the second, final (new car registrations EU6d from 01/01/2021).

Starting from September 1, 2017 all the new vehicle approvals will be made according to the Euro 6d-TEMP standard which includes measurements of pollutants based on the RDE (Real Driving Emissions) cycle instead of the previous NDEC and CO2 detection through the new WLTP methodologies (Worldwide harmonized Light vehicles Test Procedures). The same Euro 6d-TEMP approval will be mandatory for new cars registered from September 2019 and the word "TEMP" indicates the first phase of Euro 6d. In the first three years a "conformity factor" of 2.1 will be granted to manufacturers to adapt today's vehicles to the new limits, while a margin of error of 1.5 will be admitted with the introduction of the definitive Euro 6d; this will come into force on 1 January 2020 for type-approvals and 1 January 2021 for registrations.

4.3 Technology to reduce NOx emissions.

Three main technologies are available for this aim:

- EGR: recycling of gas exhaust.
- LNT: NOx traps called (Lean NOx Trap).
- SCR : Selective Catalytic Reduction.

4.3.1 EGR

The EGR (Exhaust Gas Recirculation) is a technology used to reduce emissions pollutants consisting in recycling the exhaust gases (a quantity equal to 5-15%) by re-injecting them in the combustion chamber, forcing them to pass from the exhaust manifold into the intake manifold, in order to contain internal temperatures and excesses of oxygen, the main factors of the formation of nitrogen oxides (NOx).

To obtain this recirculation, an Exhaust solenoid valve or hydrovalve Gas Recirculation (EGR) is used, it is controlled by the engine control unit via a Pulse Width Modulation signal (PWM - pulse width modulation) allowing the regulation of the quantity of exhaust gas from the relative collectors.

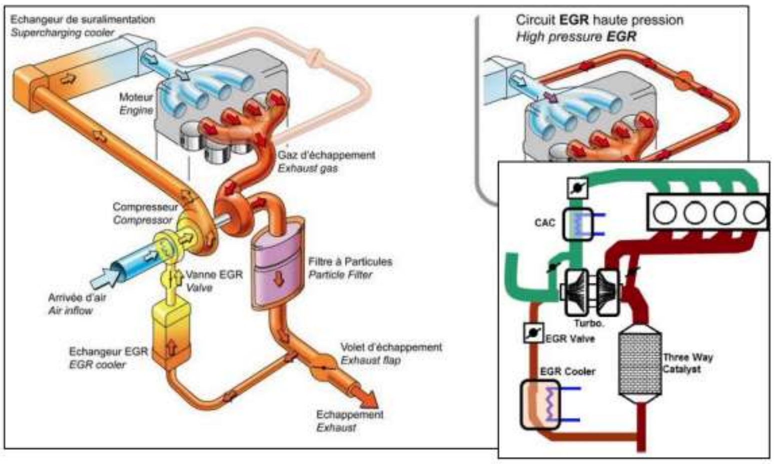


Figure 44: Low Pressure EGR System

It can be of two type, high and low pressure. In the former the gases are collected at the exit from the cylinders and re-issued directly to the suction, mixing them with the air incoming. The latter is based instead on the recovery of the exhaust gases further downstream, ie after the passage in the turbine and in the particulate filter. The flows are then cooled inside a heat exchanger and again conveyed in the turbo, mixing them with the air drawn in to obtain an increase in the boost pressure. Then they undergo a further refrigeration process in the intercooler and contribute eventually to combustion.

In the case of petrol engines, the LP-EGR system also reduces the risk of detonation, in how much a decrease of NOx extinguishes in a good part one of the causes triggering the phenomenon.

As shown in the following figure, the EGR rate can influence the fuel consumption, and as a consequence the CO2 emissions, till a rate of 5% improvement with 20% rate of EGR.

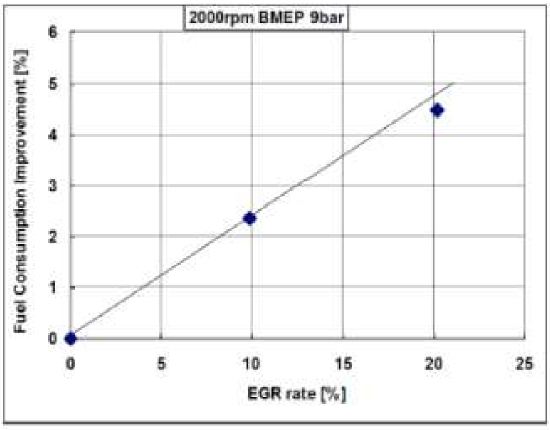


Figure 45: Fuel consumption improvement as a function of EGR rate

4.3.2. NSR (NOx Storage and Reduction)

This solution is based on the adoption of a LNT (Lean NOx Trap). This system works by storing the oxides of nitrogen for about 100 km when the mixture is lean, to release them when it is stoichiometric or rich.

Unlike a Three Way Catalyst, LNT operates discontinuously; it is made up of a monolithic structure coated with materials such as alkaline or alkaline/earth metals (Ba, K, Na, Mg, Ca) which are used both for the NOx accumulation phase and for the catalysing action of oxidation and reduction (noble metals respectively Pt and Rh). Since the NOx Trap accumulation capacity is limited, a periodic regeneration is necessary to avoid saturation phenomena with consequent loss of effectiveness of the abatement system.

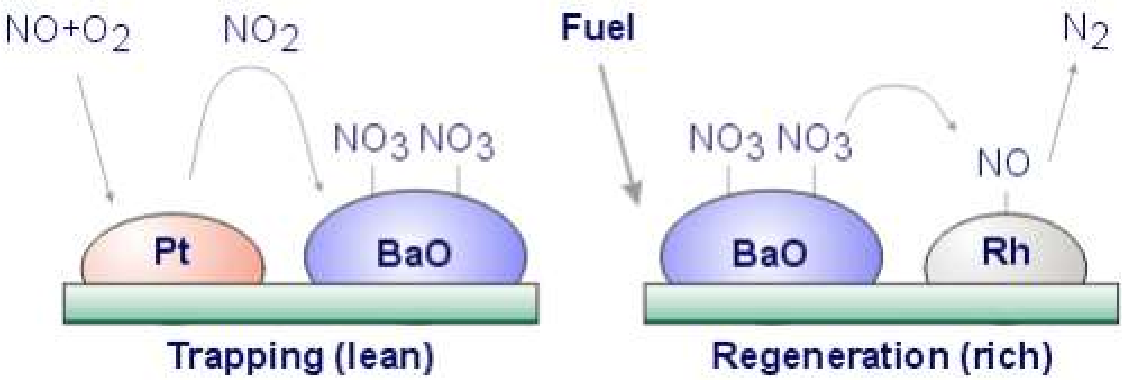


Figure 46: NOx storage and reduction dynamics

The NOx Trap are operating in a fairly wide temperature range from 200 ° C to 450-500 ° C. The lower temperature limit depends on the low oxidation kinetics of NO in NO2 at low temperatures while the upper one is determined by the instability of the nitrates which, even in conditions of lean mixture, can be decompose at high temperatures.
During the periodic regeneration (which can also take place every minute), the NOx conversion has improved thanks to a higher duration of rich-spike and low values of lambda, all at the expense of HC and CO emissions.
This system is particularly preferred, in terms of efficiency, for light vehicles with displacements of less than 2 litres.

The main disadvantages of this technology are the costs, due to presence of the noble metal Rh, the needed advanced technology for the control, and a slight increase in the fuel consumption during regeneration.

4.3.3 SCR, Selective Catalytic Reduction

For light vehicles with engine displacements greater than 2L, it is convenient to use an SCR catalyst because it allows to maintain, despite of the reduced emissions, high specific powers, that otherwise, especially for diesel engines, should be cut dramatically.

This abatement system uses a catalyst and an addictive reducing chemical agent, Ammonia or Urea, exploiting its ability to absorb oxygen, producing water vapour and N2 at the expense of NOx. Urea being less toxic, it is more widely used, despite in the automotive field, it is more commercialized the AdBlue, a 32.5% solution of high quality technical urea (low calcium content, metals etc.) in demineralized water.

This solution is injected proportionally to the quantity of exhaust gases and is precisely regulated by the ECU system thanks to the NOx sensor installed downstream of the SCR catalyst.

Figure 47: AdBlue logo

Some cars have two NOx probes, one upstream of the reducing catalyst and the other at valley: through the values found by these, the control unit is able to control the efficiency of reducing catalyst instant by instant. The SCR system for gas treatment unloading is one of the most efficient and ecological technologies, converting to the **80% of emissions**. Its design and sizing depend on different engine parameters but also from the fuel used and from the other emissions of the engine.

The system consists of:

- an additive injector placed before the filter.
- a tank for the additive and a pump that supplies the injector.
- a dosing system regulated by the control unit.
- a NOx sensor placed after the filter that evaluates the correct operation of the catalyst.
- an SCR catalyst (placed after the particulate filter).
- temperature probe.
-

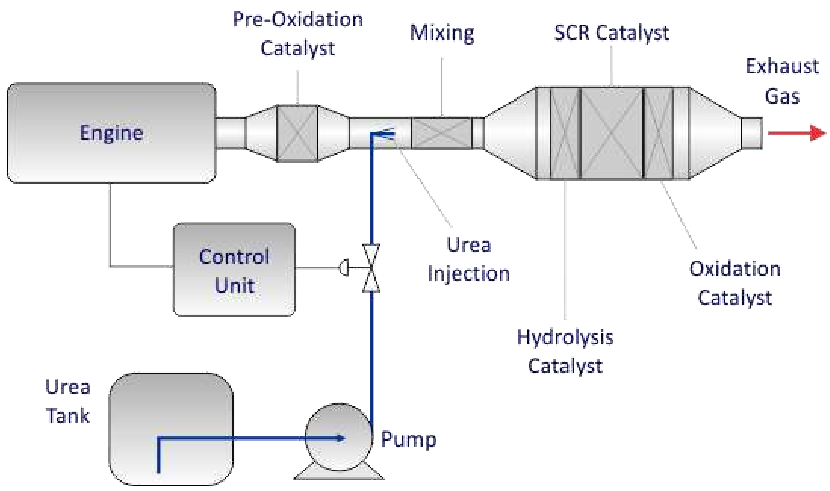


Figure 48: Selective catalytic reduction scheme

Therefore it allows to give rise to the chemical reactions of transformation of the oxides into nitrogen

$H_2NCONH_2 \rightarrow NH_3 + HNCO$

$HNCO + H_2O \rightarrow NH_3 + CO_2$

The DeNOx catalysts at HC Hydrocarbon-SCR (lean NOx reduction) allow one selective reduction of NOx by HC hydrocarbons and other compounds contained in gases of exhaust as CO and alcohols without the introduction of external reagents. They also have the merit of being little susceptible to sulphur poisoning. During the catalytic reduction the hydrocarbons are subjected to the following reactions:

$\{HC\} + NO_x \rightarrow N_2 + CO_2 + H_2O$

Those were the first cars that were available on the market in 2015 with the AdBlue technology:

- Audi: Clean-Diesel-series.
- BMW: BluePerformance-series.
- Chevrolet Cruze.

- Citroën/Peugeot: BlueHDi-engines.
- Jaguar: Modell XE.
- Mazda CX-7.
- Mercedes: BlueTec-series.
- Opel Zafira 2.0 CDTI.
- Porsche Cayenne (Type 92A) only USA.
- Volkswagen: BlueMotion Blue-Models.

There are two types of DeNOx catalysts: Active and Passive. Passive DeNOx use exclusively hydrocarbons from the fuel burned in the combustion chamber and therefore, thanks to their simplicity, reliability and low costs, the systems could be preferred, even if sometimes the HC concentrations obtainable from these sometimes are not sufficient to achieve high NOx conversions. To avoid this, the addition of additional HC in the exhaust gases (Active DeNOx).

The injection of additional fuel through a post-injection with the commonrail system does not entail high costs thanks to the flexibility of the Multijet system. The main disadvantage is the fuel consumption increase.

4.4 Testing of exhaust gas emissions.

Figure 49: Testing of a Mercedes A-Class

Exhaust emission are tested in specific laboratories in which some predefined conditions of temperature and humidity are to be maintained (20–30◦C and 30–70% of relative humidity), despite the heat released by the engine of the car. The vehicle is driven following a cycle designed to simulate city driving conditions.

Some key features of the measuring system are kept into account

- A Constant Volume Sampling (CVS) device which provides a correct dilution and mixing of the exhaust gases with ambient air, thus reproducing the diffusion conditions taking place in the atmosphere. The dilution prevents the condensation of water contained in the exhaust gases.
- Simulating the resistance to motion experienced by the car both at constant speed and in transient conditions.

In order to obtain this results, the typical laboratory is equipped with a set of standard facilities, as the followings:

- A blower driven at a fixed speed, providing a constant flow of ambient air in which the exhaust gases are diluted.
- a chassis dynamometer equipped with one or two rollers, allowing the car to be driven by a professional driver according to the selected cycle.
- a cooling fan, placed in front of the vehicle radiator and delivering an air stream proportional to the vehicle speed.
- a system displaying the theoretical and actual speed traces on a monitor, thus allowing the driver to follow the test cycle selecting the relevant gears and operating the accelerator, brake and clutch pedals. The final comparison of the traces allows one to determine the accuracy with which the cycle was followed.

- a Critical Flow Venturi (CFV), to measure the volume of the mixture ambient air/exhaust gases determined by the blower during the cycle.
- a sampling point upstream the CFV and a sampling line to collect the diluted exhaust gases in suitable bags to measure the pollutant concentrations in the vehicle exhaust.
- a sampling point of ambient air to subtract the concentration of pollutants already contained in the ambient or dilution air, the so called background concentrations.
- an emission analyser cabinet, to measure, in the respective bags, the average concentrations of pollutants contained in the exhaust gases and in the ambient air.
- a computer which, based on the measured volumes and concentrations, calculates the emissions (in grams per kilometre) according to the Directives.

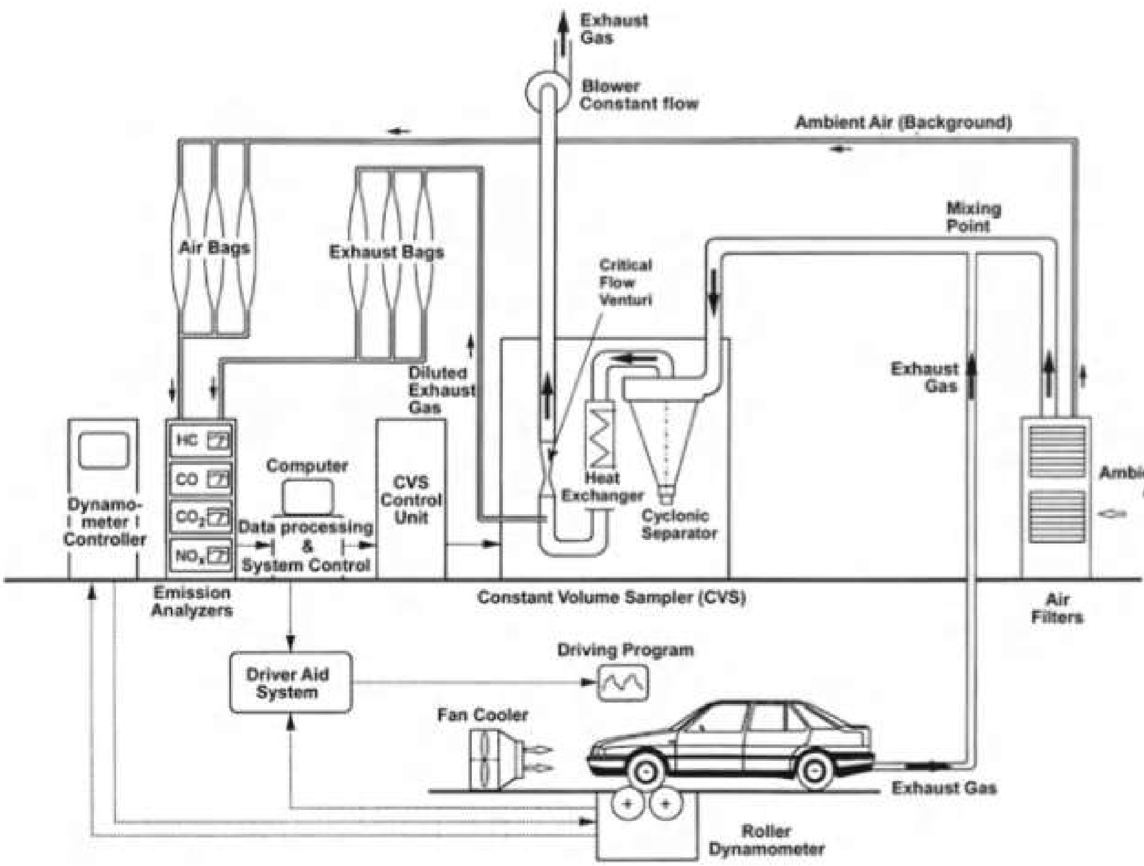


Figure 50: Typical Laboratory Equipment for Testing

The dynamometer, in addition to the rollers, is equipped with an electric brake, able to simulate the external forces that the vehicle has to face during movement: rolling resistance, aerodynamic drag and inertia forces. For a given vehicle’s configuration the resistance to motion is determined experimentally through a *coast down test* performed on a perfectly horizontal test track and in absence of wind. The coast down times are measured performing a sequence of free decelerations between two selected speeds. This sequence allows one to determine the rolling resistance and aerodynamic drag to be reproduced by the electric brake of the dynamometer, that can also simulate the car inertia, based on its curb mass value, and adding the average driver's mass of 75 kg and by an additional 25 kg mass. As already mentioned, the blower provides a constant volume flow in spite of the transient conditions, from idle to acceleration phases and assures a dilution of the exhaust gases with ambient air with a ratio ranging from 1:10 to 1:15. A heat exchanger, when needed, stabilizes the mixture temperature.

For Diesel engines an additional configuration is needed for the computation of Hydrocarbons and Particulate Matter.

- Hydrocarbons. Diesel fuel features a higher content of Carbon and its exhaust gases are emitted at a lower temperature, when compared with gasoline. This causes a further tendency to condensation along the walls of the sampling lines. To overcome this risk, the sampling lines are heated up to 190◦C.
- Particulate Matter. Since particulate emissions are not a gas, a homogeneous mixture with the dilution air must be achieved before performing their sampling. To achieve this result a dilution tunnel is added between the point at which the exhaust gases are mixed with dilution air and the sampling point; its diameter ranges between 200 and 300 mm and its length is, at least, ten times its diameter.

From the tunnel, the heated sampling lines reach, respectively, the analysers and the filter used to collect the PM sample, that is weighted before and after carrying the test.

In order to comply with Euro 5 standard, an additional device able to measure the number of dry particles, avoiding consideration of the aggregates of aerosols and water molecules, must be added. This quite complex system must be able to count the number of particles per kilometre in the size range of 0.023–2.5 µm (23– 2,500 nm).

5. DRIVIGN CYCLES.

5.1 ECE+EUDC

The ECE+EUDC test cycle, also known as the MVEG-A cycle, was used for EU type approval testing of emissions and fuel consumption from light duty vehicles [EEC Directive 90/C81/01]. The test is performed on a chassis dynamometer. The entire cycle includes four ECE segments repeated without interruption, followed by one EUDC segment. Before the test, the vehicle is allowed to soak for at least 6 hours at a test temperature of 20-30°C. It is then started and allowed to idle for 40s.

5.2 NEDC

Effectively since year 2000, the idling period has been eliminated, engine starts at 0 s and the emission sampling begins at the same time. This modified cold-start procedure is referred to as the *New European Driving Cycle* (NEDC) or as the MVEG-B test cycle.

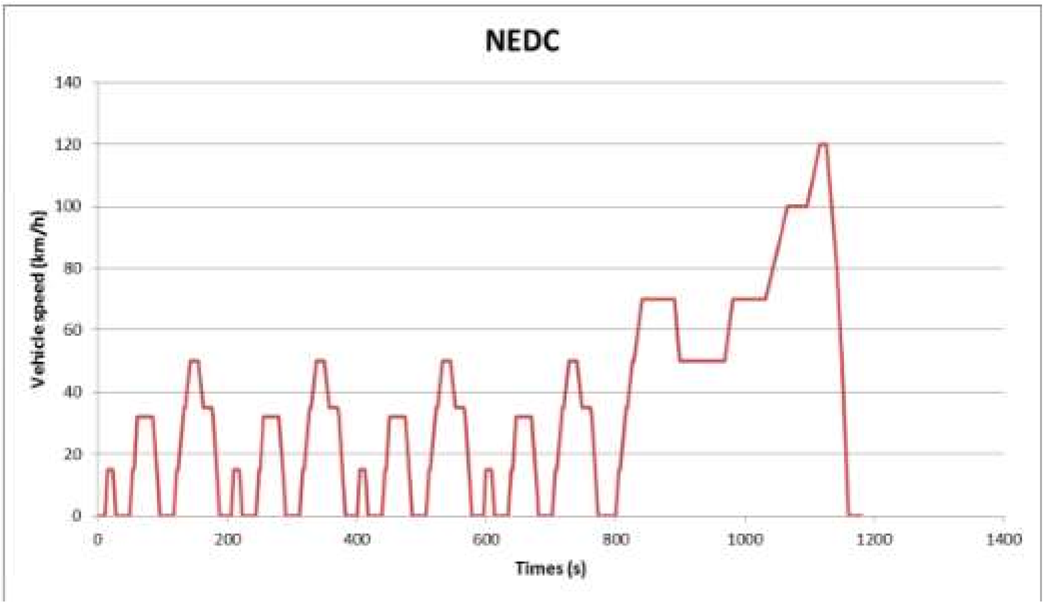


Figure 51: NEDC Speed-Time

The full test starts with four repetitions of the ECE, it is an urban driving cycle, also known as UDC. It was devised to represent city driving conditions, e.g. in Paris or Rome. It is characterized by low vehicle speed, low engine load, and low exhaust gas temperature.

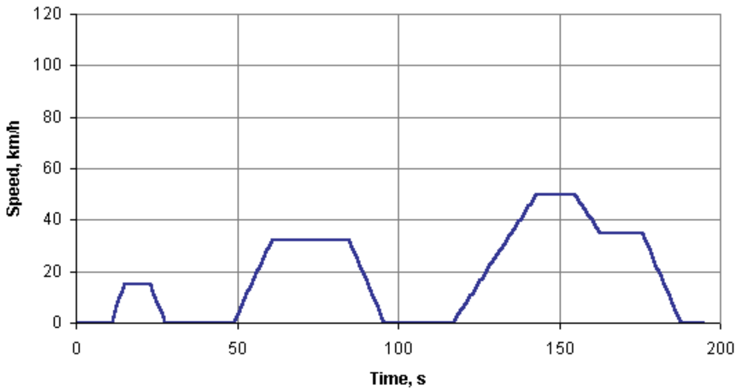


Figure 52: ECE Cycle

The EUDC (Extra Urban Driving Cycle) segment has been added after the fourth ECE cycle to account for more aggressive, high speed driving modes. The maximum speed of the EUDC cycle is 120 km/h. An alternative EUDC cycle for low-powered vehicles has also been defined with a maximum speed limited to 90 km/h, Figure 54.

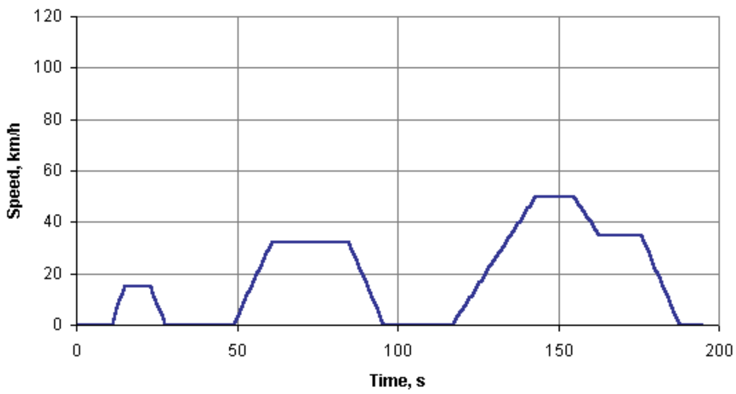


Figure 53: EUDC

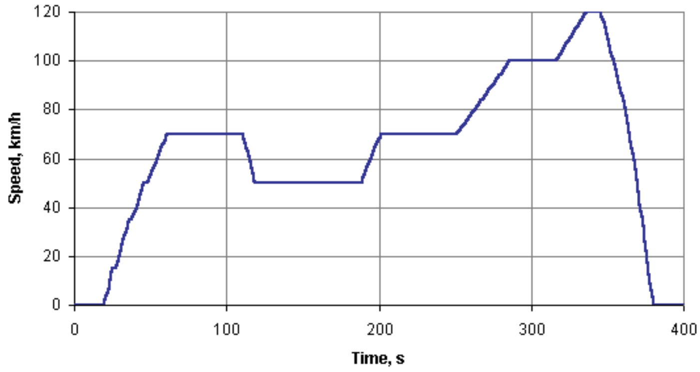


Figure 54: EUDC for low power vehicles

The final result is the NEDC cycle that is characterized by the following numbers.

Characteristics	Unit	ECE	EUDC	NEDC
Distance	km	0.9941	6.9549	10.9314
Total time	s	195	400	1180
Idle (standing) time	s	57	39	267
Average speed (incl. stops)	km/h	18.35	62.59	33.35
Average driving speed (excl. stops)	km/h	25.93	69.36	43.10
Maximum speed	km/h	50	120	120
Average acceleration	m/s^2	0.599	0.354	0.506
Maximum acceleration	m/s^2	1.042	0.833	1.042

Table 10: NEDC characteristics

5.3 Critics to NEDC.

Since the early adoption of NEDC as a standard to car manufacturers, customers' associations complained about the differences between what was declared and the real driving results of daily life. From one hand, car manufacturers could declare results that were appealing to customers, from the other hand customers were provided with information that were not perfectly realistic.

Many factors contributed to the final results. During coast down test, some tricks are adopted, as to inflate the tires more or use different types than those found on the standard car, choose a particularly favourable stretch of road, as well as a precise moment of the day and prepare the car specifically, sealing the cracks to increase the aerodynamic drag and using specific rims or wheel rims. Before each test the roller bench must be calibrated to work with maximum precision. When the NEDC was born, mechanical benches were still used, and electronic ones were used later. However, the margins of tolerance of the first, most loose, have remained unchanged even with the spread of the latter, which instead are much more precise and so more favourable correction coefficients are applied.

The state of charge of the battery is not checked and this allows you to use a 100% charged battery and to disconnect the alternator, which does not steal power to the engine (the battery in the long run discharges itself but not in the 20 minutes of the test. Vehicles that mount pre-series components are often tested, which are different from those then arrive in production destined for the market. In the NEDC approval cycle, all auxiliary systems that require power remain off, first of all air conditioning, but also the navigator, the infotainment system, the headlights, the windscreen wipers and the defroster.

The main advantage of NEDC is that it represented a standardized method to compare different automobiles. Even if results were not 100% realistic, customers could have a proper parameter to help them in the choice of their new car. Of course car manufacturers could have made available also the real driving conditions results, but it would have put them in a position of disadvantage to the ones that stuck to the NEDC.

The most tangible result for the costumer is the fuel consumption difference. Here's the results of a study of Italian cars newspaper, Auto, that compared the declared data of consumption and CO2 emission with the results obtained by their test on road.

The average consumption value measured by their Test Centre arises from the mathematical average of four cycles performed on the road: urban, suburban, motorway and 90 km/h constant, to try to get a perfect mix of the most frequent conditions of real use of the car.

BENZINA					
MODELLO	KM/LITRO EFFETTIVI	KM/LITRO DICHIARATI	EMISSIONI CO2 EFFETTIVE G/KM	EMISSIONI CO2 DICHIARATE G/KM	DIFFERENZA %
Smart Fortwo 70	**17,247**	24,4	**131,9**	93	**41,8**
Seat Leon Cupra 280	**11,84**	15,6	**202,8**	154	**31,7**
Abarth 695 Biposto	**14,558**	18,5	**184,3**	145	**27,1**
Opel Corsa 1.0	**16,255**	20,4	**133**	106	**25,5**
Volkswagen Golf R	**11,713**	14,5	**204,2**	165	**23,8**
Audi RS6 Avant	**8,241**	10,2	**275,8**	223	**23,7**
Mini JCW	**14,26**	17,5	**190,2**	155	**22,7**
Audi TT Coupé 2.0 TFSI	**12,981**	15,6	**184,9**	154	**20,1**
Volkswagen Golf GTI	**13,402**	15,6	**161,8**	139	**16,4**
Lamborghini Huracàn	**7,011**	8	**330,9**	290	**14,1**
Mercedes A 45 AMG	**13,022**	14,1	**175,3**	162	**8,2**
Porsche 911 Turbo S	**9,432**	10,1	**243**	227	**7,1**
BMW M4	**11,654**	12	**209,9**	204	**2,9**

Table 11: Differences between declared and real data of consumption for Petrol engines.

Those that are more distant from the declared cars are small and not very powerful, such as the Smart Fortwo or the Opel Corsa 1.0, while the very powerful ones have declared consumption very close to the real ones. The reason is that, starting from the assumption that the NEDC approval cycle involves very mild accelerations and therefore an almost minimal exploitation of the engine, low-powered cars can pass the test with excellent fuel consumption because the engine is used little. But in reality, when departures at the traffic light or driving on the motorway make the engine work at much more important load percentages, the distances drop drastically. Opposite for the powerful cars: during the cycle the engines are exploited little, but also in reality it is difficult for a motorist to travel always at full throttle, i.e. with 500Hp it is sufficient to march with a bit of gas to keep more than decent gaits. So, just like in the cycle, the engine works at low load rates and consumes relatively little. Obviously one of the most affecting factors is the driving style of the driver, that in the case of sporty style, could change the values drastically.

IBRIDE					
MODELLO	KM/LITRO EFFETTIVI	KM/LITRO DICHIARATI	EMISSIONI CO2 EFFETTIVE G/KM	EMISSIONI CO2 DICHIARATE G/KM	DIFFERENZA %
Porsche Panamera E-Hybrid Plug-In	**12,323**	32,3	**277**	71	**162**
Bmw I8 Plug-In	**24,324**	47,6	**95,9**	49	**95,7**
Range Rover Hybrid	**10,448**	16,1	**252,7**	164	**54,1**
Toyota Auris Hybrid	**19,908**	25,6	**123,4**	96	**28,6**
Lexus NX 300 Hybrid	**15,714**	19,2	**147,7**	121	**22,1**
Lexus IS 300 Hybrid	**18,202**	21,3	**127,5**	109	**17**

Table 12: Differences between declared and real data of consumption for Hybrid engines

Concerning hybrid plug-in cars, it was simulated the worst case scenario: low battery, with the electric that works little and therefore the ICE that consumes more. Keeping in mind, however, that the user, travelling with a charged battery, will have that mountain of 30-50 km with zero emissions electric to count on. That's why, in the specific case of plug-in hybrids (those that recharge with the plug and have more efficient and expensive lithium batteries), the real consumption is so far from the declared: in the NEDC homologation cycles, plug-ins can travel half the test using only the electric motor, lowering the total consumption by far. This explains why, for example, an 887Hp Porsche 918 Hybrid can afford to declare an average consumption of over 30 km/litre. Traditional hybrids such as Toyota and Lexus, having limited electric autonomy, cannot leverage this and therefore declare higher consumption, but that are in the end much closer to reality.

DIESEL

MODELLO	KM/LITRO EFFETTIVI	KM/LITRO DICHIARATI	EMISSIONI CO2 EFFETTIVE G/KM	EMISSIONI CO2 DICHIARATE G/KM	DIFFERENZA %
Volvo V40 Cross Country D3	**16,087**	25	**161,6**	104	**55,4**
Mini Cooper D 1.5 5P	**18,628**	28,6	**141,2**	92	**53,5**
Bmw 116d 1.5	**18,212**	27,8	**148**	97	**52,6**
Bmw 220d Active Tourer	**16,167**	24,4	**164,4**	109	**50,9**
Citroën Cactus 1.6 E-Hdi	**19,539**	29,4	**135,3**	90	**50,4**
Volvo V60 D4 Drive-E	**17,232**	25,6	**151,5**	102	**48,5**
Alfa Giulietta 2.0 Jtd 150	**16,164**	23,8	**161,9**	110	**47,2**
Bmw X5 M50d	**10,341**	14,9	**249,2**	173	**44,1**
Ford Mondeo Wagon TDCi 180	**15,515**	22,2	**167,4**	117	**43,1**
Peugeot 308 Sw 2.0 Hdi Aut.	**19,652**	23,8	**158,6**	111	**42,9**
Renault Kadjar 1.5 dCi	**18,556**	26,3	**140,2**	99	**41,7**
Kia Soul 1.6 CRDi	**14,695**	20,8	**181,1**	128	**41,5**
Fiat 500L Living 1.6 Mjt	**16,86**	23,8	**158**	112	**41,1**
Opel Meriva 1.6 CDTi 136 Cv	**16,093**	22,7	**163,5**	116	**41**
Peugeot 508 Sw 2.0 Hdi 180	**15,64**	22,2	**166,4**	118	**41**
Citroën C4 Picasso 1.6 Hdi	**17,985**	25	**141,8**	102	**39**
Nissan Qashqai 1.5 dCi	**19,011**	26,3	**136,9**	99	**38,3**
Audi A1 Sportback 1.6 TDI	**19,544**	27	**127**	92	**38,1**
DS5 BlueHdi 180	**16,439**	22,7	**151,9**	110	**38,1**
Maserati Ghibli Diesel 275	**12,329**	16,9	**216,6**	158	**37,1**
Renault Espace Initiale 1.6 dCi 160	**15,849**	21,7	**164,3**	120	**36,9**
Opel Insignia Country Tourer 2.0 Cdti	**13,759**	18,5	**193,5**	144	**34,4**
Audi Q7 3.0 TDI 272 Cv	**12,621**	16,9	**199,5**	149	**33,9**
Skoda Fabia Wagon 1.4 TDI	**19,697**	26,3	**132,1**	99	**33,5**
Mazda Cx-3 1.5D	**18,769**	25	**139,8**	105	**33,2**
Mercedes CLA 200 CDI	**17,619**	25	**138,5**	104	**33,2**
VW Golf 2.0 TDI	**18,332**	24,4	**141,1**	106	**33,1**
Seat Leon ST 2.0 TDI	**18,351**	24,4	**140,9**	106	**32,9**
Fiat Panda Trekking 1.3 Mjt	**19,298**	25,6	**136,5**	103	**32,6**
Fiat 500X 1.6 Mjt	**18,468**	24,4	**143,9**	109	**32,1**
Mazda 6 Wagon 2.2 D	**16,584**	21,7	**158,2**	121	**30,8**
Audi A3 2.0 TDI	**18,717**	24,4	**140,7**	108	**30,3**
Vw Polo 1.4 TDI	**22,622**	29,4	**114,3**	88	**29,9**
Toyota Verso 1.6 D-4D	**17,29**	22,2	**152,8**	119	**28,4**
Nissan Juke 1.5 dCi	**19,608**	25	**132,6**	104	**27,5**
Jeep Renegade 2.0 Mjt	**15,406**	19,6	**170,4**	134	**27,2**
Peugeot 2008 1.6 e-Hdi	**21,255**	27	**121,9**	96	**27**
Mercedes GLA 220 CDI 4Matic	**16,383**	20,8	**161,1**	127	**26,9**
Mazda 3 2.2 D	**19,265**	24,4	**135,4**	107	**26,6**
Mercedes GLE Coupé 350d	**11,566**	14,5	**225,5**	180	**25,3**
Audi A3 Sedan 2.0 TDI	**19,518**	24,3	**130,7**	105	**24,5**
Bmw X4 35d	**13,558**	16,7	**193,4**	157	**23,2**
VW Passat Variant 2.0 TDI 150	**17,601**	21,7	**146,6**	119	**23,2**
Skoda Yeti 2.0 TDI	**15,359**	18,9	**168,5**	137	**23**
Mercedes C 220 CDI Sw	**19,04**	23,3	**132,2**	108	**22,4**
Fiat 500X 2.0 Mjt 4X4	**14,913**	18,2	**175,8**	144	**22,1**
Volvo XC90 D5 2.0D	**14,176**	17,2	**184,4**	152	**21,3**
Bmw 220d Coupé	**18,737**	22,7	**139,2**	115	**21,1**
Suzuki Vitara 1.6 DDis 4Wd	**19,893**	23,8	**132,7**	111	**19,6**
Audi Q3 2.0 TDI Quattro 184 Cv	**15,696**	18,5	**163,7**	139	**17,8**
Land Rover Discovery Sport 2.2 Sd4	**14,061**	16,4	**185,4**	159	**16,6**
Range Rover Evoque 2.2 Sd4	**13,515**	15,4	**198,2**	174	**13,9**
Skoda Superb 2.0 TDI 190 4X4	**18,524**	20	**141,3**	131	**7,9**
Hyundai Santa Fe 2.2 CRDi	**14,214**	15,1	**184,8**	174	**6,2**
Subaru Outback 2.0 D-S	**16,265**	16,4	**160,3**	159	**0,8**

Table 13: Differences between declared and real data of consumption for Diesel engines

From the analysis of the data of Diesel emerges a value on all. On average, cars consume 30% more than the declared value. An average that comes from peaks of over 50% waste for some BMW and Volvo models, up to cars like Land Rover, Skoda, Hyundai and Subaru that are very close to reality. There is no precise logic, unlike hybrids and gasoline ones, but some consideration can be drawn anyway. It is always the case that the more a car is powerful, the more it will have real consumption close to those declared from the fact that the engine, so in the NEDC cycle as in reality, is almost always exploited to not very high workloads. On the contrary, a low-powered diesel will exceed the approvals with excellent values just in light of the poor exploitation of power during the NEDC, but, when the user will have to ask more to a less powerful engine, consumption will increase.

5.4 WLTP normative and WLTC approval cycle.

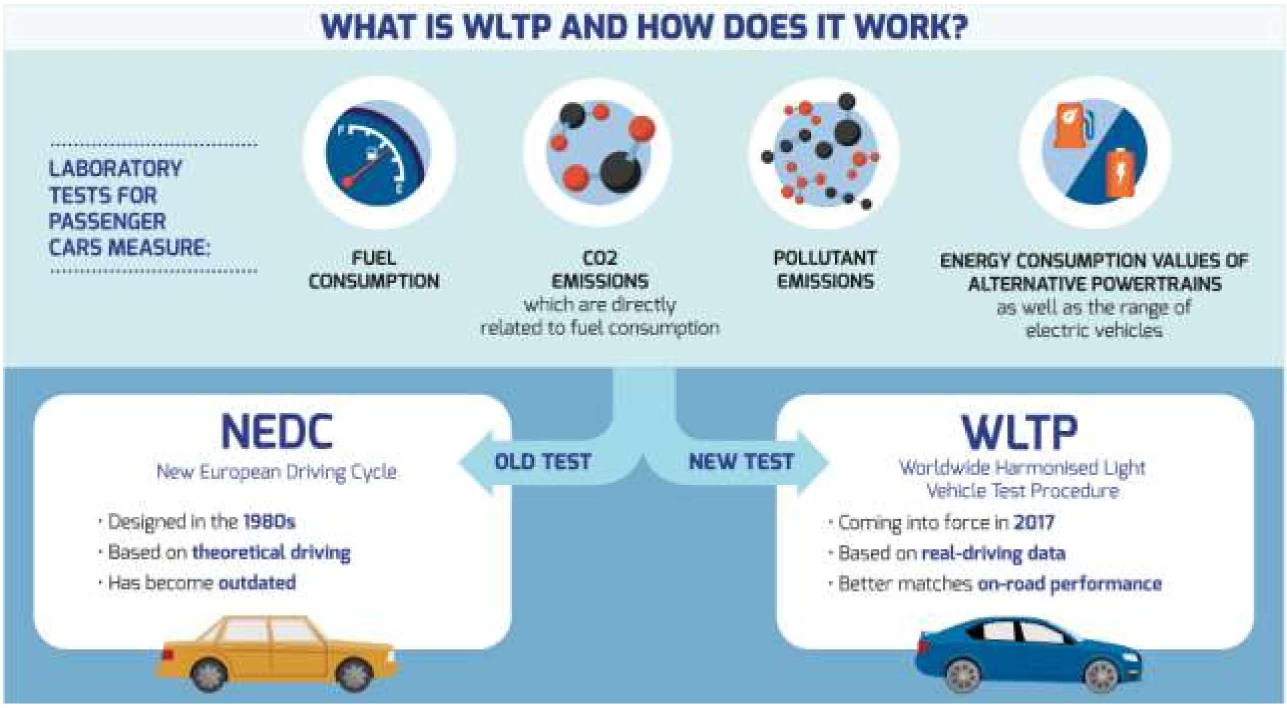


Figure 55: Basics of WLTP

The awareness of an obsolete homologation cycle that does not conform to the real driving conditions and far from correctly estimating consumption and emissions generated, as mentioned above, has led the European Community to formulate new approval procedures with the consequent application of a universal driving cycle since 2008. The other fundamental characteristic that is required in the drafting of these new regulations under which vehicles are tested is the unification at a global level, so that the same parameters can be met. The final document has been drafted by experts from the European Union, Japan, and India under guidelines of UNECE World Forum for Harmonization of Vehicle Regulations

The final result is the WLTP, acronym for Worldwide Harmonized Light Vehicles Test Procedure. The test is valid since September 1st 2017 only for vehicles that require an approval (brand new models). Within a year, from 1 September 2018, all newly registered cars will have to meet the same requirements. Until September 2019 a limited number of unsold vehicles in stock, tested according to NEDC, could still be sold.

Ideally a test cycle for homologation should be practical (not too long or complicated for its execution in the laboratory), repeatable and reproducible and above all, it should provide representative results of the vehicle behaviour in real life. The harmonized low-power test cycle was derived using data collected in five different regions: EU + Switzerland, United States of America, India, Korea and Japan on different types of road (urban, rural, motorway) and in different driving conditions (peak, off-peak, weekend) covering a wide range of vehicle categories. The vehicle traffic data were collected from 441 vehicles equipped with on-board data acquisition systems capable of estimating speed and acceleration, as well as motor rpm at a frequency of at least 1 Hz. A special software has been developed to process the huge amount of recorded data (about 815000 km of data) and for the statistical analysis of the parameters. Processing of raw data initially involves filtering and thinning; filtration was applied to remove noise due to measurement errors and was performed using a standard smoothing algorithm.

The final version of the WLTC is not a single cycle, but a set of cycles to be used on vehicles with different characteristics. The following table shows the acceleration and speed profiles for the three different categories in which the tested vehicles are grouped

WLTC	Phase	Duration [s]	Stop duration [s]	Distance [m]	Stop percentage [%]	Maximum speed [km/h]	Avg speed without stop [km/h]	Average speed with stop [km/h]	Relative Positive Acceleration [kWs/(kg•km)]
Class 3	Low	589	156	3095	26.5	56.5	25.7	18.9	0.2046
	Medium	433	48	4756	11.1	76.6	44.5	39.2	0.1904
	High	455	31	7162	6.8	97.4	60.8	56.7	0.1223
	Ex-High	323	7	8254	2.2	131.3	94.0	92.0	0.1249
	WLTC	1800	242	23266					
Class 2	Low	589	155	3101	26.3	51.4	25.7	19.0	0.1605
	Medium	433	48	4737	11.1	74.7	44.3	39.4	0.1236
	High	455	30	6792	6.6	85.2	57.5	53.7	0.1218
	Ex-High	323	7	8019	2.2	123.1	91.4	89.4	0.0913
	WLTC	1800	240	22649					
Class 1	Low	589	154	3330	26.1	49.1	27.6	20.4	0.0908
	Medium	433	48	4767	11.1	64.4	44.6	39.6	0.0743
	WLTC	1022	202	8098					

Table 14: WLTC data per class

5.4.1 Classification of vehicles.

It is based on the ”mass in running order”, that is the mass of the vehicle, with the tank filled at least for 90% of its capacity, including the mass of the driver, fuel and liquids, fitted with the standard equipment in accordance with the specifications of the manufacturer and, when fitted, the mass of the bodywork, the cab, the coupling, the spare wheel and the tools.

The PMR parameter is defined as the ratio of rated power (W) / curb mass (kg). The curb mass (or kerb mass) means the “unladed mass” as defined in ECE R83. The cycle definitions may also depend on the maximum speed (v_max), which is the maximum speed of the vehicle as declared by the manufacturer (ECE R68) and not any use restriction or safety based limitation. Cycle modifications are allowed to accommodate drivability problems for vehicles with power to mass ratios close to the borderlines or with maximum speeds limited to values below the maximum speed required by the cycle.

- 1: vehicles with mass in running order ≤ 22W / kg.
- 2: > 22 W / kg but ≤ 34 W / kg.
- 3: > 34 W / kg. In turn divided into two sub-categories according to their maximum speed, the value that outlines the transition from one category to another is 120 km/h.

5.4.2 Cycles.

A WLTC driving cycle, depending on the class of vehicle tested, may include the following sections at different speeds and durations:

- Low speed phases (Low): 589 s.
- Medium speed phases (Medium): 433 s.
- High speed phases (High): 455 s.
- Super high speed phases (Extra High): 323 s.

Category	PMR, W/kg	v_max, km/h	Speed Phase Sequence
Class 3b	PMR > 34	v_max ≥ 120	Low 3 + Medium 3-2 + High 3-2 + Extra High 3
Class 3a		v_max < 120	Low 3 + Medium 3-1 + High 3-1 + Extra High 3
Class 2	34 ≥ PMR > 22	-	Low 2 + Medium 2 + High 2 + Extra High 2

Class 1	PMR ≤ 22	-	Low 1 + Medium 1 + Low 1

Table 15: WLTP Cycle Classes Division

5.4.2.1 Class 1 Cycle

With the lowest power-to-mass ratio, Class 1 is representative of vehicles driven in India. A complete cycle for Class 1 vehicles consists of a low speed phase (Low 1), a medium speed phase (Medium 1) and an additional low speed phase as shown in Figure..

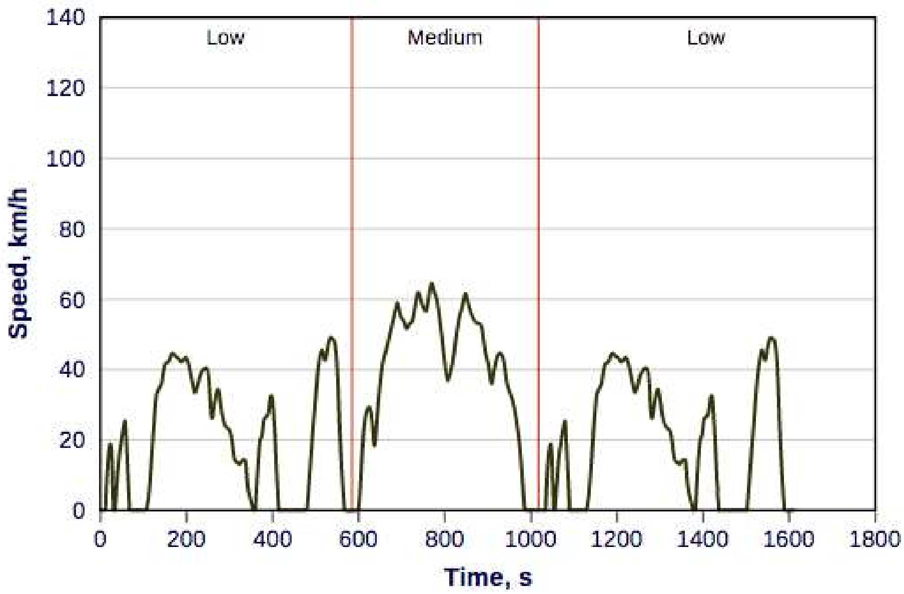


Figure 56: WLTP Class 1 cycle speed-time diagram

Phase	Duration	Stop Duration	Distance	p_stop	v_max	v_ave w/o stops	v_ave w/ stops	a_min	a_max
	s	*s*	*m*		*km/h*	*km/h*	*km/h*	*m/s²*	*m/s²*
Low 1	589	154	3330	26.1%	49.1	27.6	20.4	-1.00	0.76
Medium 1	433	48	4767	11.1%	64.4	44.6	39.6	-0.53	0.63
Low 1	589	154	3330	26.1%	49.1	27.6	20.4	-1.00	0.76
Total	**1611**	**356**	**11428**						

Table 16: WLTP class 1 cycle data

5.4.2.2 Class 2 Cycle

Class 2 is representative of vehicles driven in India and of low power vehicles driven in Japan and Europe.

A complete cycle for Class 2 vehicles consists of a low speed phase (Low 2), a medium speed phase (Medium 2), a high speed phase (High 2) and a super high speed phase (Extra High) 2), as shown in Figure 61.

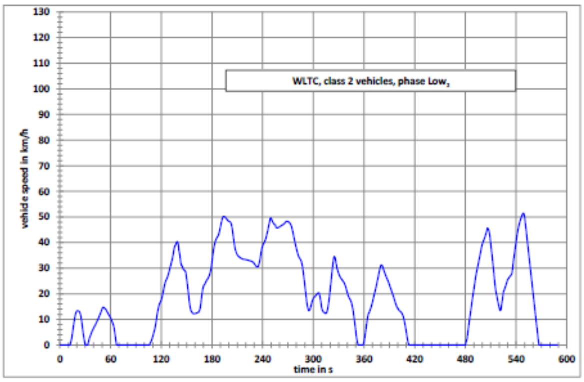


Figure 57: WLTP Class 2 cycle, phase low speed-time diagram

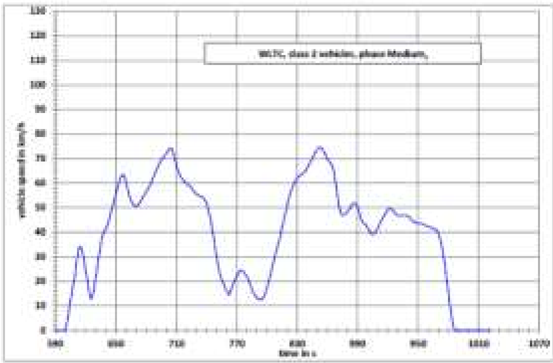


Figure 58: WLTP Class 2 cycle, phase medium speed-time diagram

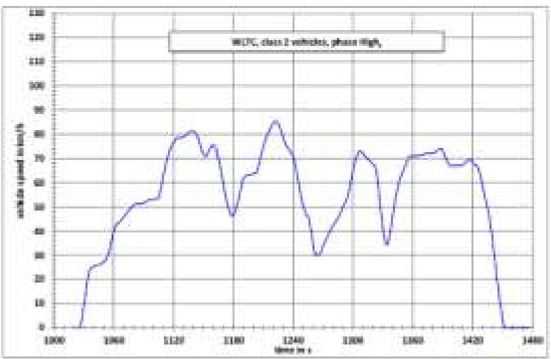


Figure 59: WLTP Class 2 cycle, phase High speed-time diagram

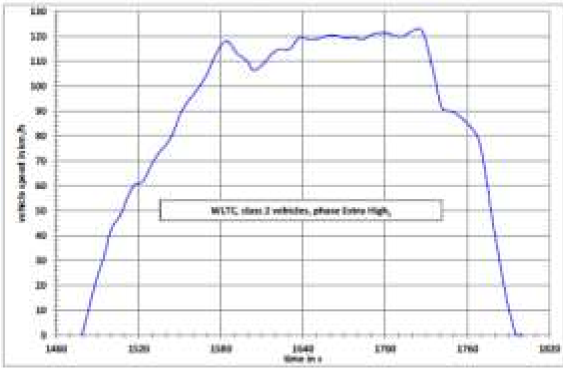


Figure 60: WLTP Class 2 cycle, phase Extra High speed-time diagram

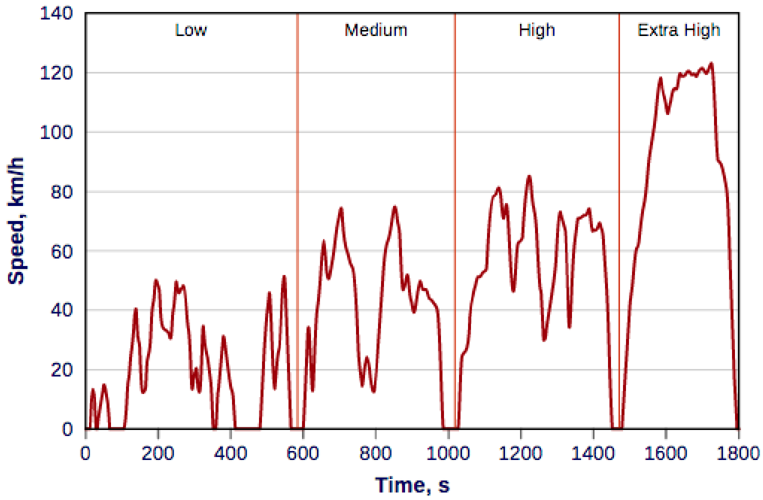


Figure 61:WLTP Class 2 cycle total speed-time diagram

Phase	Duration	Stop Duration	Distance	p_stop	v_max	v_ave w/o stops	v_ave w/ stops	a_min	a_max
	s	*s*	*m*		*km/h*	*km/h*	*km/h*	*m/s²*	*m/s²*
Low 2	589	155	3101	26.3%	51.4	25.7	19.0	-0.94	0.90
Medium 2	433	48	4737	11.1%	74.7	44.3	39.4	-0.93	0.96
High 2	455	30	6792	6.6%	85.2	57.5	53.7	-1.11	0.85
Extra-High 2	323	7	8019	2.2%	123.1	91.4	89.4	-1.06	0.65
Total	**1800**	**240**	**22649**						

Table 17. WLTP class 2 cycle data

5.4.2.3 Class 3 Cycle

With the highest power-to-mass ratio, Class 3 is representative of vehicles driven in Europe and Japan.

A complete cycle for Class 3 vehicles consists of a low speed phase (Low 3), a medium speed phase (Medium 3), a high speed phase (High 3) and a super high speed phase (Extra High) 3), as shown in Figure 62. The Medium and High phases are slightly different depending on the subcategory according to the maximum speed, to which the tested vehicle belongs; the difference is in terms of the average speed reached in these phases.

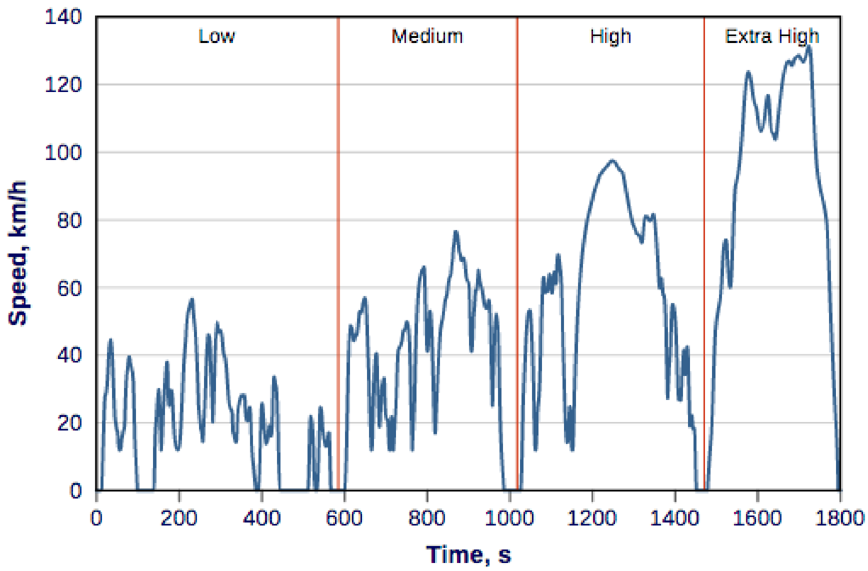


Figure 62: WLTP class 3cycle speed-time diagram

Phase	Duration	Stop Duration	Distance	p_stop	v_max	v_ave w/o stops	v_ave w/ stops	a_min	a_max
	s	*s*	*m*		*km/h*	*km/h*	*km/h*	*m/s²*	*m/s²*
Class 3b (v_max ≥ 120 km/h)									
Low 3	589	156	3095	26.5%	56.5	25.7	18.9	-1.47	1.47
Medium 3-2	433	48	4756	11.1%	76.6	44.5	39.5	-1.49	1.57
High 3-2	455	31	7162	6.8%	97.4	60.8	56.7	-1.49	1.58
Extra-High 3	323	7	8254	2.2%	131.3	94.0	92.0	-1.21	1.03
Total	**1800**	**242**	**23266**						
Class 3a (v_max < 120 km/h)									
Low 3	589	156	3095	26.5%	56.5	25.7	18.9	-1.47	1.47

Medium 3-1	433	48	4721	11.1%	76.6	44.1	39.3	-1.47	1.28
High 3-1	455	31	7124	6.8%	97.4	60.5	56.4	-1.49	1.58
Extra-High 3	323	7	8254	2.2%	131.3	94.0	92.0	-1.21	1.03
Total	**1800**	**242**	**23194**						

Table 18: WLTP class 3 cycle data

5.4.3 Cycle Modifications

For some vehicles, it may not be possible to follow speed/time requirements of the cycle. The reasons for this are:

Vehicles with power to mass ratios close to the borderlines between Class 2 and Class 3 vehicles or very low powered vehicles in Class 1 may not be able to achieve the accelerations required to maintain cycle speed. In these cases, a downscaling procedure can be applied to reduce the maximum acceleration rates to improve driveability. A consequence of this procedure is a reduction of maximum cycle speeds.

Some vehicles may have a maximum speed limited to a value lower than the maximum speed of the downscaled cycle. In these cases, the vehicle shall be driven with its maximum speed in those cycle periods where the cycle speed is higher than the maximum speed of the vehicle. An example of vehicles for which this applies is Class 3a vehicles over the Extra-High 3 phase.

Some vehicles may not be able to follow the speed trace of the downscaled cycle within the required tolerance for specific periods. In these cases the vehicle shall be driven with the accelerator control fully activated during these periods. In these cases, driving trace violations are permitted.

5.4.4 WLTP for Hybrid and Electrics Vehicles.

The International Council of Clean Transportation's (ICCT) researches highlighted that the gap between official data and real data has been growing progressively since 2001, but above all that the most worrying gap belongs to hybrid vehicles. The electric double-feed vehicles such as plug-ins have up to 215% higher consumption than the approved ones. The discrepancy between the homologated values and the data actually recorded at the NEDC is attributed, which provides optimal conditions to obtain consumption even less than 50% from real ones and in plug-in hybrids the phenomenon could be further accentuated. The weak point according lies in the management of the battery, which would be able to help the engine and reduce consumption in the most crucial phases, such as departures. While in real driving the accumulator of a hybrid car is never 100% charged, in the homologation tests instead the battery is completely pre-loaded and never completely discharging in the 11 km of the test, the combustion engine is ignited accordingly just for a very short time. In real driving after the first 30-50 km it is necessary to switch to diesel or gasoline, increasing consumption and emissions excessively. That's why in the case of plug-ins the test is even more fallacious. The WLTC should be able to fill all the gaps in the NEDC cycle and minimize the gap between declared and actual consumption.

For purely battery operated **electric vehicles**, this means that the higher average speed of the new test cycle leads to a higher energy consumption. This energy is stated, however, not in litres, but in kilowatt-hours (kWh) per 100 kilometres. The measurement is carried out as prescribed in the previous fuel consumption measurement specification: the battery must be fully charged at the start of test bench test. Immediately after testing, test engineers reconnect the vehicle to a charger. The cable is equipped with an electricity meter. This meter measures the total amount of current, which has the advantage that the battery’s energy losses during c harging are detected as well. The resulting value is divided by the range determined in test bench testing.

Figure 63: Tesla Model S

Roll-out of the WLTP signifies a major change for **plug-in hybrid vehicles**, which have both an electric drive and a combustion engine and can be externally recharged. These vehicles complete the test several times. They start up with a full battery. The cycle is repeated until the battery is empty. The combustion engine operates for a longer time each cycle. Emissions are measured with each cycle. This is followed by a measurement with an empty battery in which the drive energy originates solely from the combustion engine and regenerative braking. This multi-stage measurement can not only be used to determine fuel consumption and CO2 emissions more precisely, but the electrical range and total range as well. The CO2 value to be determined is then calculated as the ratio of the electrical range to the total range. At the same time, a so-called “utility factor” (UF) is introduced.

Figure 64: Toyota Prius Plug-in

The UF represents the proportion of vehicle distance travelled electrically. In the case of pure electric vehicles, a UF of 100% applies. In the case of traditional internal combustion engines, the UF is 0%. In the case of plug-in hybrid vehicles, the UF increases with their electrical range. Lawmakers can use the UF to evaluate a vehicle’s ability to drive without emissions. The higher the electrical range, the lower the CO_2 emissions. This is quite close to real-life conditions since the driver of a plug-in hybrid will have to refuel less often when he or she has sufficient current available, e.g. to drive typical commutes purely electrically. In practice, the actual consumption behaviour of a car with plug-in hybrid drive will vary widely from one user to another. In the case of long-distance trips, the electrical distance travelled is negligible and the consumption will be on a par with the traditional combustion engine. On the other hand, many short-distance trips and commutes can be covered almost entirely electrically, with actual fuel consumption close to 0 l/100 km.

5.5 Differences between NEDC and WLTP.

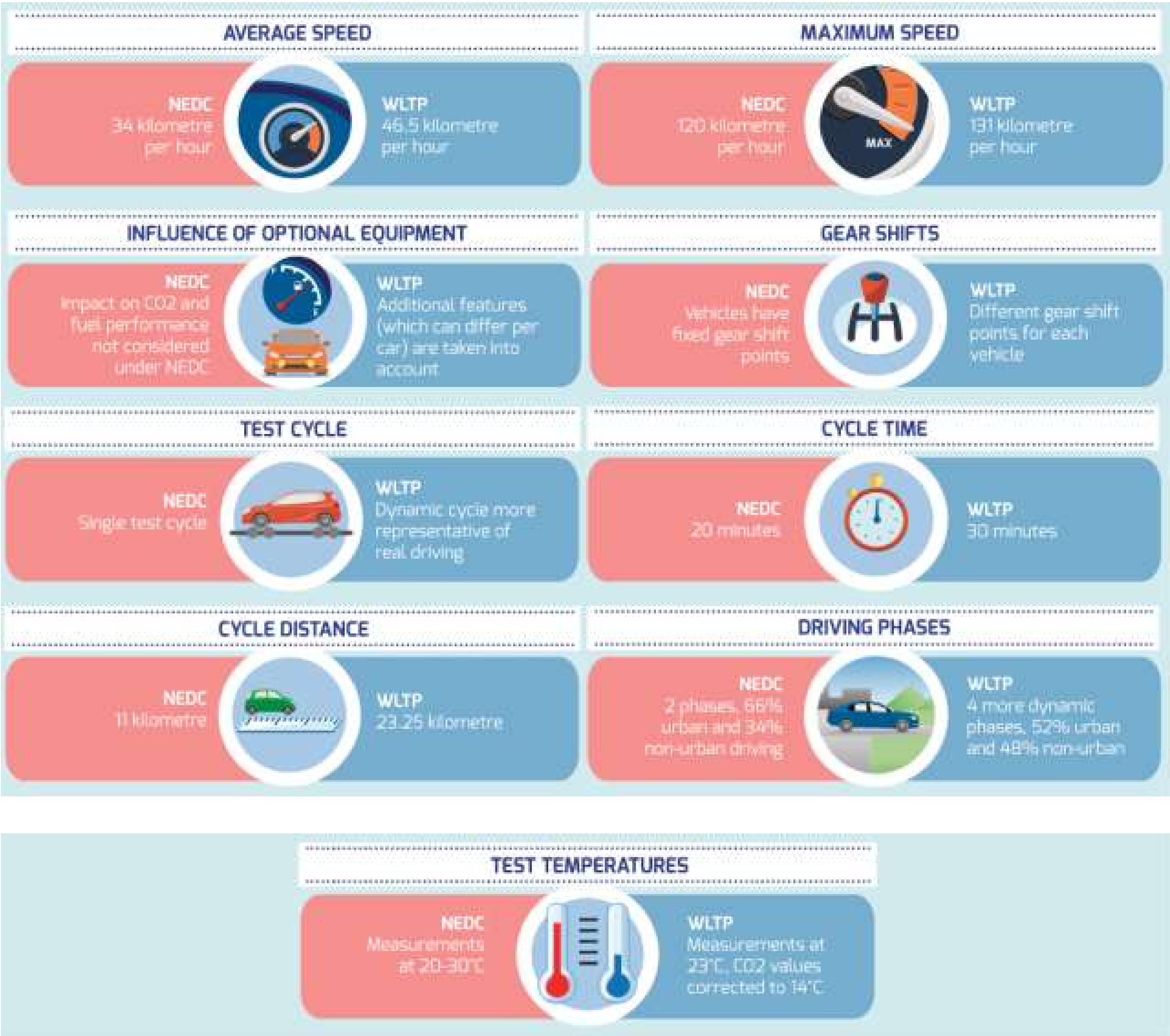
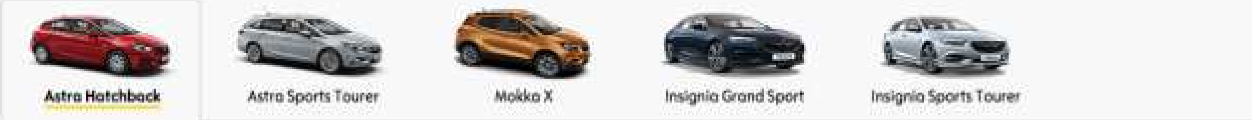


Figure 65: Difference between NEDC and WLTP

As a result, the emissions and consumption of new omologated cars are gonna rise in the next 2 years. From the point of view of customers, this translates into a more realistic data and a clearer information above buying phase.
On the other hand, manufactorers are gonna deal with a major concern, how to fit into the new regulations with the stricter cycle, and how to properly inform their customers about this sudden increase of fuel consumption.

In the meantime some of them have alreasy started informing their customers about this change, as the case of Opel, that in its website provides all the data and differences of consumption of its car, as shown in the following figure (Opel Astra example).

From the data above is easily inferrable the effect of the adoption of the WLTC comapred to NEDC.



Vehicle Combination	NEDC*				WLTP driving cycle based**
Engines and Transmissions	Official fuel consumption in l/100 km*			Official specific CO_2 emission in g/km*	Fuel Consumption Range**
Petrol	urban	extra-urban	combined	combined	
B 14 XE (100 hp), Manual 5-speed	7.5-7.3	4.4-4.2	5.5-5.4	128-124	9.0-5.4
B 10 XFL ecoFLEX (105 hp) Start/Stop, Manual 5-speed	5.2-5.1	3.9-3.8	4.4-4.3	102-99	7.3-4.8
B 10 XFL ecoFLEX (105 hp) Start/Stop (MTA), Automatic / Manual 5-Speed	5.2-5.0	3.8-3.6	4.3-4.1	99-96	8.2-4.7
B 14 XFL (125 hp), Manual 6-speed	7.3-7.1	4.5-4.4	5.5-5.4	128-124	9.4-5.6
B 14 XFL (125 hp) Start/Stop, Manual 6-speed	6.3-6.2	4.3-4.2	5.1-4.9	117-114	8.5-5.0
B 14 XFT (150 hp), Manual 6-speed	7.3-7.1	4.5-4.4	5.5-5.4	128-124	9.7-5.7
B 14 XFT (150 hp) Start/Stop, Manual 6-speed	6.3-6.2	4.3-4.2	5.1-4.9	117-114	8.5-5.0
B 14 XFT (150 hp) Start/Stop (AT6), Automatic 6-speed	7.2-7.1	4.5-4.4	5.5-5.4	127-124	9.9-5.8
B 16 SHT (200 hp) Start/Stop, Manual 6-speed	8.0-7.9	5.0-4.9	6.1-6.0	141-138	10.0-6.0
Diesel					
B 16 DTC (95 hp), Manual 6-speed	4.2-4.2	3.3-3.3	3.7-3.6	97-95	6.1-4.3
B 16 DTE (110 hp), Manual 6-speed	4.2-4.2	3.3-3.3	3.7-3.6	97-95	6.4-4.3
B 16 DTE (110 hp) Start/Stop, Manual 6-speed	4.0-3.9	3.3-3.1	3.5-3.4	93-90	5.9-4.2
B 16 DTU ecoFLEX (110 hp) Start/Stop, Manual 6-speed	3.9-3.8	3.2-3.1	3.4-3.3	91-88	5.7-4.2
B 16 DTH (136 hp) (AT6), Automatic 6-speed	5.7-5.5	3.8-3.7	4.5-4.4	119-115	7.8-4.6
B 16 DTH (136 hp) Start/Stop, Manual 6-speed	4.6-4.4	3.5-3.4	3.9-3.8	103-99	6.1-4.3
B 16 DTR BiTurbo (160 hp) Start/Stop, Manual 6-speed	5.1-5.0	3.6-3.4	4.1-4.0	109-106	6.7-4.3

Figure 66: Opel Astra data comparison between NEDC e WLTP

An additional analysis carried out by Jato on various models, shows how the average increase in g/km of CO2 is inbewteen 6 and 18 %.

MAKE	MODEL	VERSION	g/km OF CO_2 JUL-17	g/km OF CO_2 OCT-17	CHANGE OCT vs JUL in g/km	CHANGE OCT vs JUL in %	TYPE OF CHANGE
BMW	X5	3.0 XDRIVE30D A	156	183	27	17%	NEDC Corr
BMW	X5	3.0 M50D A	173	205	32	18%	NEDC Corr
BMW	X5	3.0 XDRIVE40D A	157	183	26	17%	NEDC Corr
BMW	X6	3.0 M50D	174	206	32	18%	NEDC Corr
BMW	X6	3.0 XDRIVE30D A	157	183	26	17%	NEDC Corr
BMW	X6	3.0 XDRIVE40D A	163	183	20	12%	NEDC Corr
PEUGEOT	308	1.2 PURETECH 130 ALLURE SW	111	124	13	12%	NEDC Corr
PEUGEOT	308	1.2 PURETECH 130 ACTIVE SW	106	121	15	14%	NEDC Corr
PEUGEOT	308	1.2 PURETECH 130 ALLURE	107	120	13	12%	NEDC Corr
PEUGEOT	308	1.2 PURETECH 130 ACTIVE	104	117	13	13%	NEDC Corr
VOLVO	XC60	2.0 D4 MOMENTUM GEARTRONIC 4WD	133	144	11	8%	NEDC Corr
VOLVO	XC60	2.0 D5 INSCRIPTION GEARTRONIC 4WD	144	152	8	6%	NEDC Corr
VOLVO	XC60	2.0 D4 INSCRIPTION GEARTRONIC 4WD	133	148	15	11%	NEDC Corr
VOLVO	XC60	2.0 D4R DESIGN GEARTRONIC 4WD	133	148	15	11%	NEDC Corr
VOLVO	XC60	2.0 D5R DESIGN GEARTRONIC 4WD	144	152	8	6%	NEDC Corr
VOLVO	XC90	2.0 D5 AWD INSCRIPTION GEARTRONIC	149	163	14	9%	NEDC Corr
VOLVO	XC90	2.0 D5 AWD MOMENTUM GEARTRONIC	149	173	24	16%	NEDC Corr
VOLVO	XC90	2.0 D5 AWR R DESIGN GEARTRONIC	149	163	14	9%	NEDC Corr

Source: JATO Dynamics Ltd

Figure 67: BMW, Peugeot and Volvo NEDC and WLTP comparison, by Jato

5.6 American driving cycles

5.6.1 FTP-75 cycle

The FTP cycle (for Federal Test Procedure) has been created by US EPA (Environmental Protection Agency) to represent a commuting cycle with a part of urban driving including frequent stops and a part of highway driving.

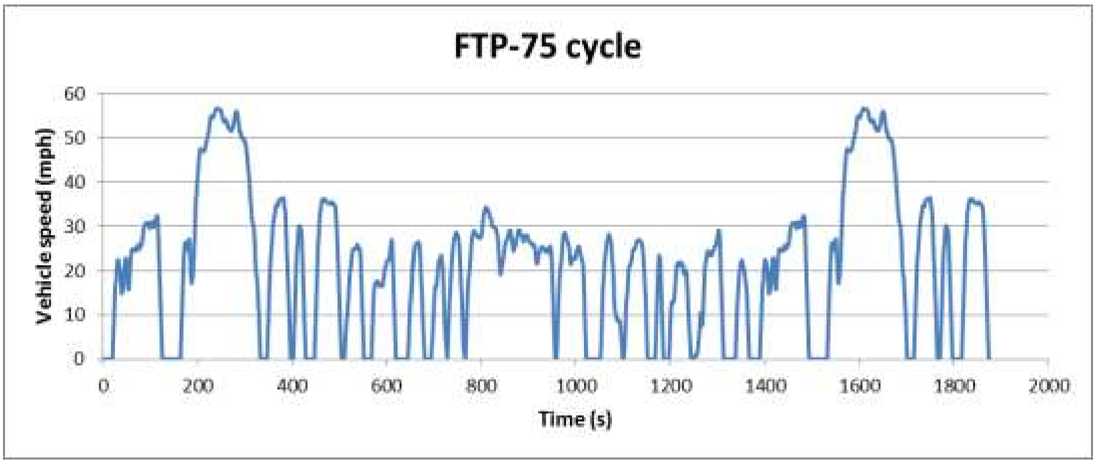


Figure 68: FTP-75 Cycle, speed-time diagram

Here are the main characteristics of the cycle:

- Distance travelled: 17.77 km (11.04 miles).
- Duration: 1874 seconds.
- Average speed: 34.1 km/h (21.2 mph).

5.6.2 USA Standard Emission Tier 2

The EPA's Tier 2 emission standards that were phased in over a period of four years, beginning in 2004, for LDV/LLDTs, with an extension of two years for HLDTs, were in full effect starting from MY 2009 for all new passenger cars and light-duty trucks, including pickup trucks, vans, minivans and sport-utility vehicles. The Tier 2 standards were designed to significantly reduce ozone-forming pollution and PM emissions from passenger vehicles regardless of the fuel used and the type of vehicle. The Tier 2 standards were implemented along with the gasoline fuel sulphur standards in order to enable emissions reduction technologies necessary to meet the stringent vehicle emissions standards. The gasoline fuel sulphur standard mandates the refiners and importers to meet a corporate average gasoline sulphur standard of 30 ppm starting from 2006.

The EPA Tier 2 emissions standard requires each LDV/LDT vehicle manufacturer to meet a corporate average NOx standard of 0.07g/mile (0.04 g/km) for vehicles being sold for a given model year. Furthermore, the Tier 2 emissions standard consists of eight sub-bins, each one with a set of standards to which the manufacturer can certify their vehicles provided the corporate sales weighted average NOx level over the full useful life of the vehicle (10 years/120,000 miles/193,121 km), for a given MY of Tier 2 vehicles, is less than 0.07g/mile (0.04 g/km). The corporate average emission standards are designed to meet the air quality goals allowing manufacturers the flexibility to certify some models above or below the standard, thereby enabling the use of available emissions reduction technologies in a cost-effective manner as opposed to meeting a single set of standards for all vehicles.

Bin#	Intermediate life (5 years / 50,000 mi)					Full useful life (10 years/120,000 mi)				
	NMOG*	CO	NO_x	PM	HCHO	NMOG*	CO	NO_x†	PM	HCHO
Temporary Bins										
11 MDPV[c]						0.28	7.3	0.90	0.12	0.032
10[a,b,d,f]	0.125 (0.160)	3.4 (4.4)	0.40	-	0.015 (0.018)	0.156 (0.230)	4.2 (6.4)	0.60	0.08	0.018 (0.027)
9[a,b,e,f]	0.075 (0.140)	3.4	0.20	-	0.015	0.090 (0.180)	4.2	0.30	0.06	0.018
Permanent Bins										
8[b]	0.100 (0.125)	3.4	0.14	-	0.015	0.125 (0.156)	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	-	0.015	0.09	4.2	0.15	0.02	0.018
6	0.075	3.4	0.08	-	0.015	0.09	4.2	0.10	0.01	0.018
5	0.075	3.4	0.05	-	0.015	0.09	4.2	0.07	0.01	0.018
4	-	-	-	-	-	0.07	2.1	0.04	0.01	0.011
3	-	-	-	-	-	0.055	2.1	0.03	0.01	0.011
2	-	-	-	-	-	0.01	2.1	0.02	0.01	0.004
1	-	-	-	-	-	0	0	0	0	0

* *for diesel fueled vehicle, NMOG (non-methane organic gases) means NMHC (non-methane hydrocarbons)*
† *average manufacturer fleet NO_x standard is 0.07 g/mi for Tier 2 vehicles*
a *Bin deleted at end of 2006 model year (2008 for HLDTs)*
b *The higher temporary NMOG, CO and HCHO values apply only to HLDTs and MDPVs and expire after 2008*

Figure 69: Light-duty vehicle, light-duty truck and medium-duty passenger vehicle - EPA Tier 2 exhaust emissions standards in g/miles

Manufacturers must comply with 4000 mile and full useful life SFTP (Supplementary Federal Test Procedure) standards. The 4000 mile SFTP standards are shown in Table 2.3.

Vehicle Class [1)]	US06		SC03	
	NMHC + NO_x	CO	NMHC + NO_x	CO
LDV/LDT1	0.14	8.0	0.20	2.7
LDT2	0.25	10.5	0.27	3.5
LDT3	0.40	10.5	0.31	3.5
LDT4	0.60	11.8	0.44	4.0

1) *Supplemental exhaust emission standards are applicable to gasoline and diesel-fueled LDV/Ts but are not applicable to MDPVs, alternative fueled LDV/Ts, or flexible fueled LDV/Ts when operated on a fuel other than gasoline or diesel*

Figure 70: US-EPA 4000 mile SFTP standards in g/mi for Tier 2 vehicles

In-use testing of light duty vehicles under the Tier 2 regulation involves testing of vehicles on a chassis dynamometer that have accumulated at least 50,000 miles during in-use operation, to verify compliance with FTP and SFTP emissions standards at intermediate useful life. There has been no regulatory requirement in the United States to verify compliance of Tier 2 vehicles for emissions standards over off-cycle tests such as on road emissions testing with the use of PEMS

equipment, similar to what is being mandated for heavy-duty vehicles via the engine in- use compliance requirements.
Fuel economy and CO2 emission ratings as published by the US-EPA and the US Department of Energy (DOE) are based on laboratory testing of vehicles while being operated over a series of five driving cycles on a chassis dynamometer specified in more detail in. Originally, only the 'city' (FTP-75) and 'highway' cycles were used to determine vehicle fuel economy, however, starting with model year 2008 vehicles the test procedure has been augmented by three additional driving schedules, specifically, 'high-speed' (i.e. US06), 'air conditioning' (i.e. SC03 with air conditioning turned on), and 'cold temperature' (i.e. FTP-75 at 20°F ambient temperature) driving cycles. Vehicle manufacturer are required to test a number of vehicles representative of all available combinations of engine, transmission and vehicle weight classes being sold in the US. The fuel economy label provides distance-specific fuel consumption and CO2 emissions values for 'city', and 'highway' driving as well as a combined value (i.e. Combined MPG) calculated as a weighted average of 55% 'city' and 45% 'highway' driving, allowing for a simplified comparison of fuel efficiency across different vehicles.

Driving Schedule Attributes	Test Schedule				
	City	Highway	High Speed	AC	Cold Temp.
Trip type	Low speeds in stop-and-go urban traffic	Free-flow traffic at highway speeds	Higher speeds; harder accel. and braking	AC use under hot ambient conditions	City test w/ colder outside temperature
Max. speed [mph]	56	60	80	54.8	56
Avg. speed [mph]	21.2	48.3	48.4	21.2	21.2
Max. accl. [mph/s]	3.3	3.2	8.46	5.1	3.3
Distance [miles]	11	10.3	8	3.6	11
Duration [min]	31.2	12.75	9.9	9.9	31.2
Stops [#]	23	None	4	5	23
Idling time [%] [1)]	18	None	7	19	18
Engine Startup [2)]	Cold	Warm	Warm	Warm	Cold
Lab temperature [°F]	68 - 86	68 - 86	68 - 86	95	20
Vehicle AC	Off	Off	Off	On	Off

[1)] *Idling time in percent of total test duration*
[2)] *Maximum fuel efficiency is not reached until engine is in warmed up condition*

Figure 71: Fuel economy and CO2 emissions test characteristics

6. ROAD TO EUROPE 2020

6.1 Climate & Energy Package

The Europe 2020 strategy is the EU's agenda for growth and jobs for the current decade. It emphasises smart, sustainable and inclusive growth as a way to strengthen the EU economy and prepare its structure for the challenges of the next decade.

Climate change and energy are closely interlinked, due to the fact that production and consumption of energy generated from fossil fuels substantially contribute to global warming. In 2009, the EU committed to limiting the average global temperature rise to 2 °C above pre-industrial levels, through reducing greenhouse gas (GHG) emissions, as unchecked climate change would erode the foundations of modern society. This commitment was reinforced and strengthened in 2015 by the Paris Agreement's aspiration to limit the temperature increase to 1.5°C above pre-industrial levels. Through its climate change and energy targets the Europe 2020 strategy aims to shift the EU towards a low-carbon economy based on renewable energy sources and energy efficiency.

The Europe 2020 strategy targets on climate change and energy sets three objectives for climate and energy policy, to be reached by 2020:

1. Reducing GHG emissions by at least 20 % compared with 1990 levels.
2. Increasing the share of renewable energy in final energy consumption to 20 %.
3. Moving towards a 20 % increase in energy efficiency.

These targets are also known as the '20-20-20' targets. The Europe 2020 strategy's three climate and energy targets are interrelated and mutually support one another. The EU is currently debating the climate and energy targets for 2030. With the Clean Energy for All Europeans legislative package of November 2016, the European Commission has tabled a comprehensive set of legislative proposals and measures to further develop climate and energy policy after 2020.

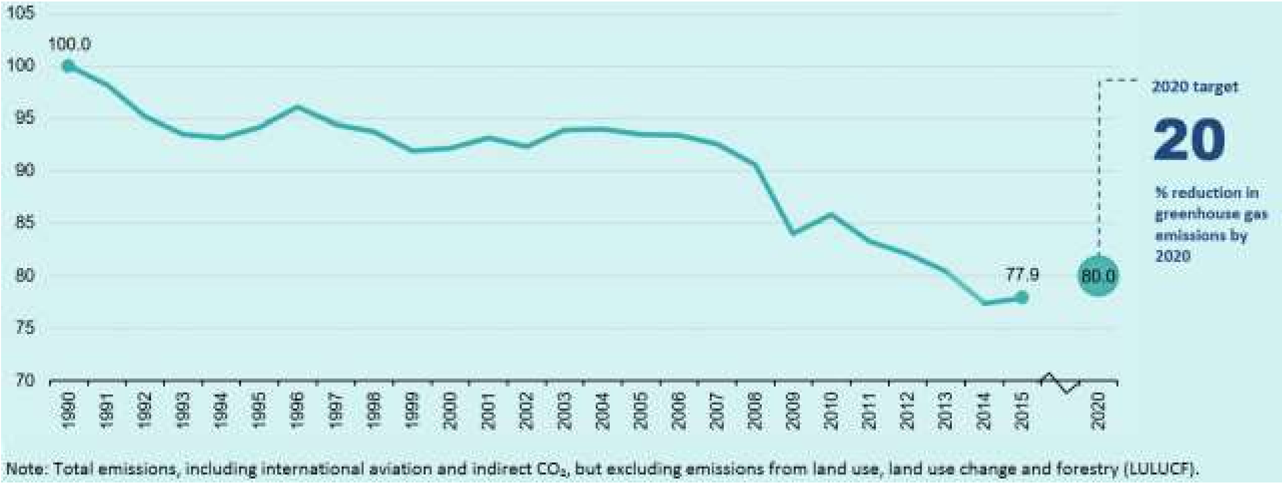


Figure 72. Greenhouse gas emissions, EU-28, 1990–2015, (Index 1990=100)
Source: Eurostat online data code (t2020_30)

Road transport is the second largest source of greenhouse gas emissions in the EU after energy generation; it contributes about one fifth of total carbon dioxide emissions.
This is one of the few sectors where emissions have increased rapidly over the last 20 years, with the exception of the 2008-2010 period. In the period between 1990 and 2010, emissions increased by 22.6%; this increase has acted as a brake on the progress of the European Union in reducing global greenhouse gas emissions, down by 15.4%, in fact the only cars are responsible for about 12% of the EU's CO2 emissions. Although there have been significant improvements in vehicle technology in recent years, particularly in fuel savings resulting in lower CO2 emissions, these have not been sufficient to counteract the effects of increased traffic and vehicle size.

According to the regulation, average CO2 emissions from cars should not exceed 130 grams of CO2 per km by 2015, phased in gradually since 2012. This represents a 19% reduction from the 2006 level (161.3 g of CO2 per km) and is expected to fall further to 95 g/km by 2020, a reduction of 20% compared to 1990. At least 95% of new cars will have to meet this requirement by that year and 100% from 2021 onwards. The achievement of these objectives will help Member States to achieve the greenhouse gas savings they have promised to deliver by 2020 of the Climate and Energy package.
Each producer gets an annual target based on the average mass of all his new cars registered in Europe in a given year. From 2012, producers must ensure that 65% of new passenger cars registered in Europe each year have average emissions that are below their respective targets. The percentage rises to 75% in 2013, to 80% in 2014 and to 100% in 2015; analogous speech for the process of further reduction from today to the imminent 2020.

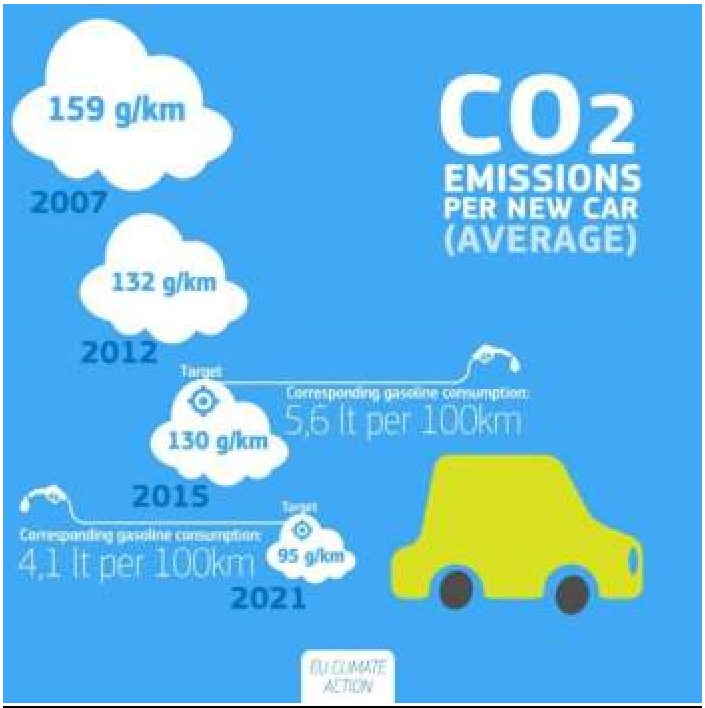


Figure 73: CO2 emissions per new car (avg.) and relative fuel consumption

The indicative emissions are established for each car based on its mass in relation to the limit curve; it is set up in such a way that only the fleet average is regulated, so manufacturers will still be able to make vehicles with emissions above their targets in accordance with the norm, always if these are offset by other vehicles that are below the limit values. Therefore, for heavier cars, emissions higher than lighter cars are allowed, while ensuring that the target of 95 g/km in 2020 is met.

In order to comply with the regulation, a manufacturer must ensure that the weighted average sales average of all his new machines does not exceed the limit value curve. The curve for passenger cars is defined so that, compared to today, the emissions of heavy vehicles will have to be reduced more than those of light vehicles.

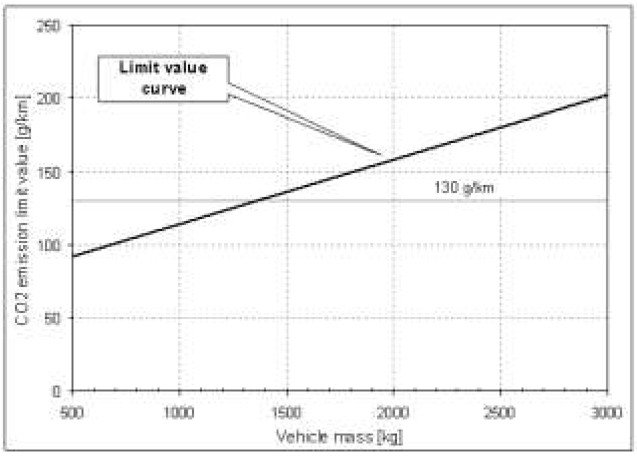


Figure 74: Limit Value Curve

The formula for the limit value curve is:

Specific CO_2 emissions allowed = T + a × (M - M0).

M = mass in kg of the vehicle;
M0 (average mass of vehicles) = 1372 kg for the calendar years 2012-2015. M0 = 1392.4 kg from 2016;
a (coefficient) = 0.0457 from 2012 until 2019. a = 0.0333 from 2020;
T (CO_2 emissions target) = 130 g / km from 2012 until 2019. T = 95 g / km from 2020.

According to the European Agency of Environment, cars sold in 2014, on average, emitted 2.6% less CO_2 emissions than those sold in 2013 and almost 7 g/km less than the 2015 target.
The average level of emissions of a new car sold in 2014 was 123.4 grams of carbon dioxide per kilometer, in 2015 had CO_2 average emissions were 119.5 g CO_2/km, which was 8.0 % below the 2015 target of 130 g CO_2/km, and 27 % lower than in 2004. From the time the monitoring was started under the legislation in force in 2010, emissions decreased by 17 g/km (12%); this means a fuel consumption of about 5.6 litres per 100 km of petrol or 4.9 L/100 km of diesel.

Manufacturer	Registrations (a)	Average mass (kg) 2015	Average CO_2 emissions (g CO_2 /km)					
			2015	2014	2013	2012	2011	2010
Automobiles Peugeot	857 467	1 260	104	110	115	121	128	131
Automobiles Citröen	618 627	1 244	106	111	116	123	126	131
Renault SAS	984 981	1 263	106	108	110	121	129	134
Toyota Motor Europe NV SA	585 335	1 315	108	113	116	122	126	129
Hyundai Assan Otomotiv Sanayi ve Ticaret AS (b)	155 201	1 079	114	113	112	-	-	-
Nissan International SA	548 778	1 366	115	115	131	137	142	147
Skoda Auto AS	585 559	1 275	116	121	125	132	135	139
Fiat Group Automobiles SPA	703 654	1 159	116	116	116	117	118	125
Seat SA	332 988	1 248	117	117	119	127	125	131
Ford-Werke GmbH	993 383	1 333	118	121	122	129	132	137
Volkswagen AG	1 655 413	1 391	119	124	127	133	135	140
Magyar Suzuki Corporation Ltd	125 532	1 161	120	123	126	128	128	137
Kia Motors Corporation (c)	228 179	1 309	122	125	128	129	137	143
Volvo Car Corporation	266 351	1 703	122	126	131	142	151	157
Automobile Dacia SA	378 487	1 204	123	125	127	137	143	145
Daimler AG	800 325	1 561	125	131	137	143	153	160
Bayerische Motoren Werke AG	887 020	1 569	126	131	134	138	144	146
Mazda Motor Corporation	194 754	1 362	127	128	134	142	147	149
Adam Opel AG	915 125	1 387	127	130	132	133	134	140
Audi AG	717 955	1 590	127	131	133	138	145	152
Honda of the UK Manufacturing Ltd	104 595	1 453	133	134	145	156	161	162
Hyundai Motor Manufacturing Czech SRO (b)	236 932	1 454	135	140	138	-	-	-
Kia Motors Slovakia SRO (c)	151 884	1 438	138	141	140	-	-	-
Jaguar Land Rover Limited	172 792	1 997	164	178	182	-	-	-

Note: (a) These are total number of registrations in the EU-28, not the registrations used for the calculation of the target and of the average emissions (see Annex 1).

(b) In previous years Hyundai appeared as a single manufacturer.

(c) In previous years Kia appeared as a single manufacturer (Kia Motors Corporation).

(d) In previous years Jaguar and Land Rover appeared as two separate manufacturers.

Figure 75. Main statistics for large car manufacturers (more than 100.000 vehicles registrations per year)

Source: European Environment Agency Report

Figure 75 presents data (number of registrations, average mass and average emissions) for 2015 for all large manufacturers individually, i.e. those that registered more than 100 000 vehicles in 2015. Manufacturers are ranked according to their 2015 average specific emissions (low to high). In total, these manufacturers sold 13.2 million new cars in the EU-28 in 2015, equivalent to 96 % of the total new registrations. The average emissions of each of those manufacturers in previous years (2009–2014) are also included in the table.

In 2015, 20 large manufacturers had average emissions below 130 g CO2/km, whereas in 2014 only 16 manufacturers were below this value. Eleven of these 20 manufacturers had average emissions below 120 g CO2/km and 4 of them had average emissions below 110 g CO2/km. The average emissions of these large manufacturers varied from 103.7 g to 164.0 g CO2/km.

Automobiles **Peugeot** and Automobiles **Citroën** had significantly improved their performance from the previous year by 5.8 and 5.0 g CO2/km respectively, reaching the two lowest average CO2 emissions (104 and 106 g CO2/km respectively) among the large manufacturers. This is mainly related to the improved performances of the conventional vehicles. The percentages of vehicles emitting less than 95 g CO2/km were 18 % and 12 % in 2014 and increased to 28 % and 22 % in 2015 respectively for Automobiles Peugeot and Automobiles Citroën. For both manufacturers, diesel vehicles represented around 60 % of their fleet. These diesel vehicles had low emissions (102 and 105 g CO2/km) and were small in mass (1 360 and 1 349 kg) compared with the average diesel fleet in EU-28 (Tables 3.1 and 3.5). Their petrol cars are also smaller in mass than the European average (around 1 100 kg).

Renault's average emissions decreased by almost 15 g CO2/km from 2012 to 2015. In 2015, 94 % of Renault vehicles emitted less than 130 g CO2/km and 36 % of those vehicles emitted less than 95 g CO2/km Almost 2% of the Renault fleet were BEVs; they contributed to reduce the average CO2 emissions by 2 g CO2/km. Diesel vehicles were almost 60 % of the Renault fleet, with average emissions of 102.2 g CO2/km, one of the lowest among all cars manufacturers.

Toyota Motor Europe continued to produce some of the lowest-emitting cars, as one third of its fleet had emissions below 95 g CO2/km (41 %). The Toyota Motor Europe fleet comprised 76.8 % petrol vehicles, with the lowest average emissions (104.4 g CO2/km) of the large manufacturers. This was mainly related to the high proportion of hybrid vehicles emitting between 75 and 100 g CO2/km.

Nissan made significant improvements in CO2 emissions in 2013 and 2014 (almost 16 g CO2/km), but was stable in 2015. The good performance of recent years is related to the increased number of electric vehicles (which corresponds to a CO2 saving of almost 3 g CO2/km), to the downsizing of thefleet (30–40 kg lighter than in 2013) and to the improved performances of the conventional vehicles (the percentage of the vehicles emitting less than 130 g CO2/km was 82 % in 2015, 86 % in 2014 and only 56 % in 2013).

As in previous years, in 2015 **Fiat** had one of the lowest average masses among the large manufacturers (1 159 kg), but was eighth in terms of emissions. The proportion of AFVs in Fiat's fleet is quite high (11 %), but mainly composed of those vehicles that run on LPG and NG.
NG vehicles registered in Italy emitted 96.8 g CO2/km while LPG vehicles emitted 113.7 g CO2/km, around 6.4 g CO2/km less than petrol vehicles and slightly more than diesel vehicles (113.2 g CO2/km). Since the emissions of NG and LPG vehicles are becoming comparable to those of conventional vehicles, Fiat performances did not improve in 2015: its vehicles emitted on average 116 g CO2/km, as in 2014 and 2013, and only 1 g CO2/km less than in 2012.

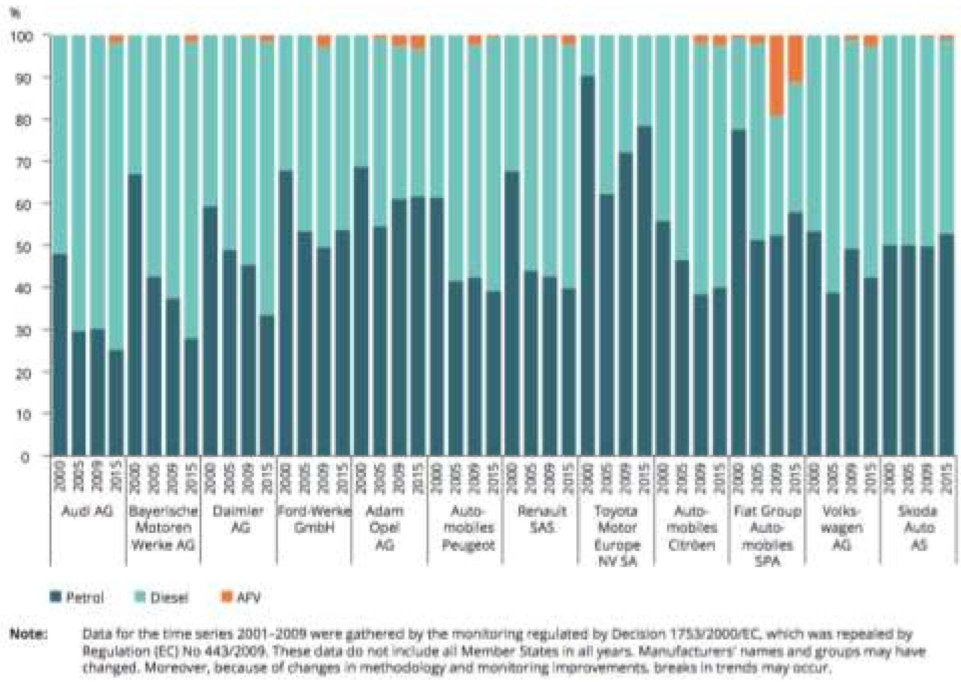


Figure 76: Fuel type for the largest manufacturers (more than 500.000 registrations per year)

Source: European Environment Agency Report

Similarly, the average emissions from vans sold in 2015 were 168.3 g CO2/km, below the 2017 target of 175 g CO2/km. This represents a reduction of 6.5 % since monitoring commenced in 2012. In order to meet their respective future targets, i.e. 147 g CO2/km for vans by 2020 and 95 g CO2/km for cars by 2021, the average CO2 emissions need to continue decreasing at a similar pace.

By 2021 the average to be reached gradually from the previous year, is 95 grams of CO2 per kilometer equivalent to a fuel consumption of about 4.1 L/100 km of gasoline or 3.6 L/100 km of diesel.
The targets for 2015 and 2021 therefore represent a reduction of 18% and 40% respectively, compared to the 2007 average of 158.7g / km.

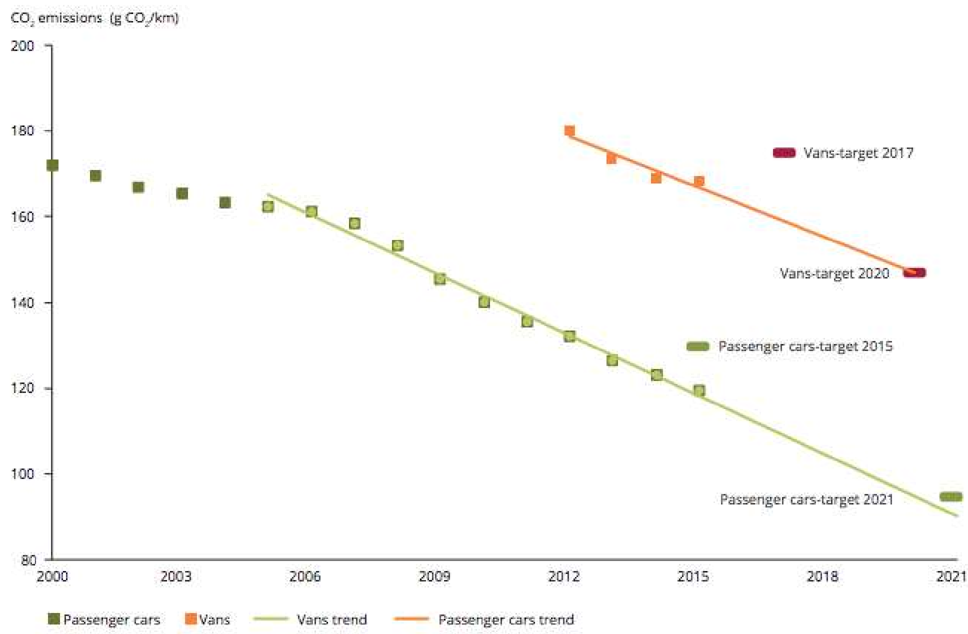


Figure 77: Average CO2 emissions historical development and targets for new passenger cars and vans in EU-28

Source: European Environment Agency Report

Some manufacturers are well on track to reach the 2021 target. For instance, Automobiles Peugeot, Renault SAS, Automobiles Citroën and Toyota are already very close to their 2021 targets: they need to reduce their average emissions by less than 16 g CO2/km from 2015 to 2021.

Other manufacturers still have to make considerable progress to achieve their 2021 targets.

Figure 78 presents the progress of the manufacturers responsible for more than 500 000 vehicles a year in terms of annual percentage changes for two periods: 2000–2009 and 2009–2015. These rates are compared with the expected reductions for respecting the 2021 target set by the regulation.

For these manufacturers the rate of progress required from now till 2021 is in general lower than or comparable to the rate that has been achieved in the last 4 years, since Regulation (EU) No 443/2009 came into force. There are only four manufacturers for which the progress rates required in the 2015–2021 period are greater than in the previous years. The figure also shows that the highest improvements were achieved over the 2009–2015 period.

All this data were computed according to the NEDC, this implies that the effort requested to engineers to comply with the new emissions norms is actually bigger and more energy and cost demanding.

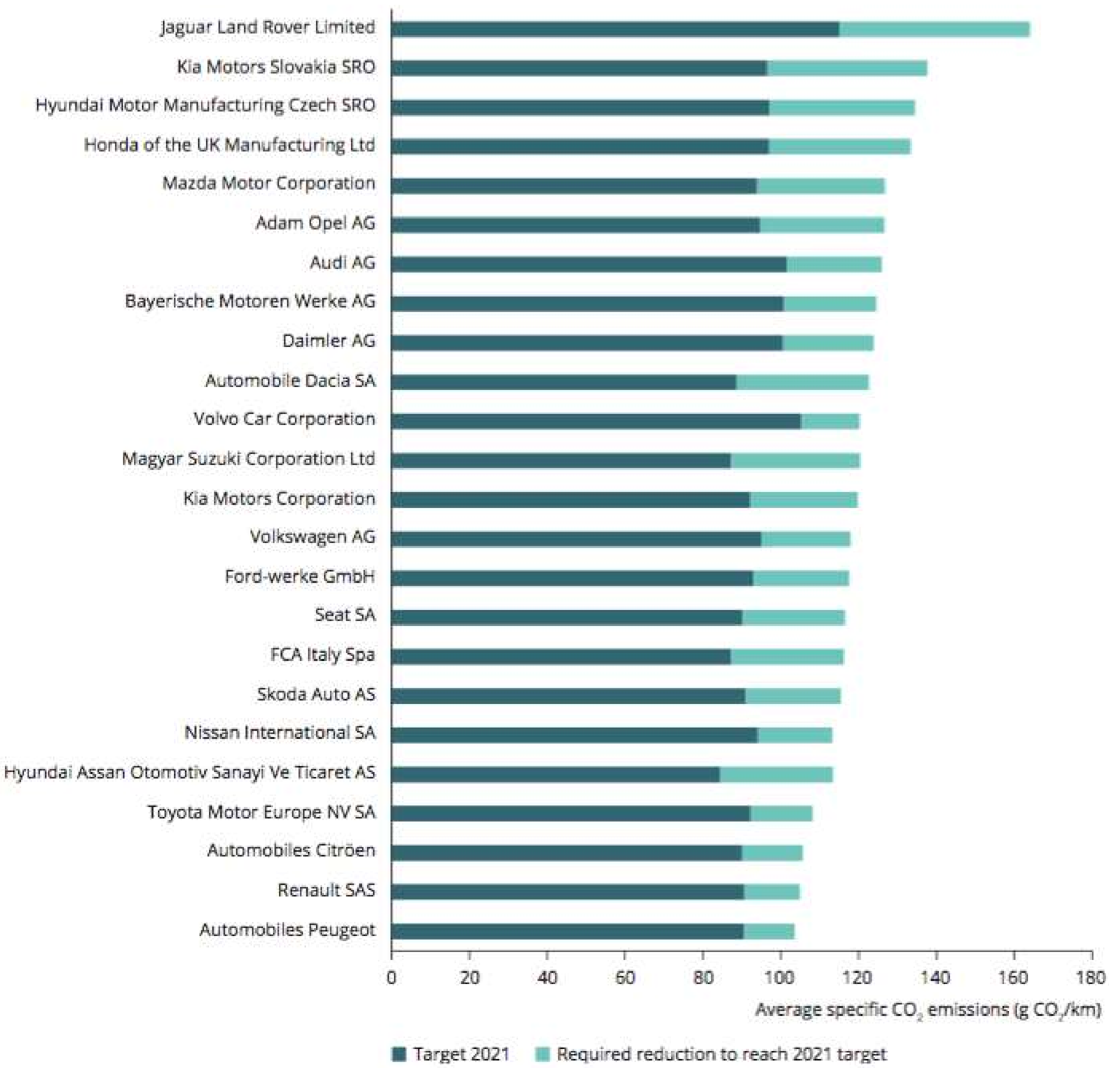


Figure 78. Comparison of past and future progress towards meeting the 2021 target

Source: European Environment Agency Report

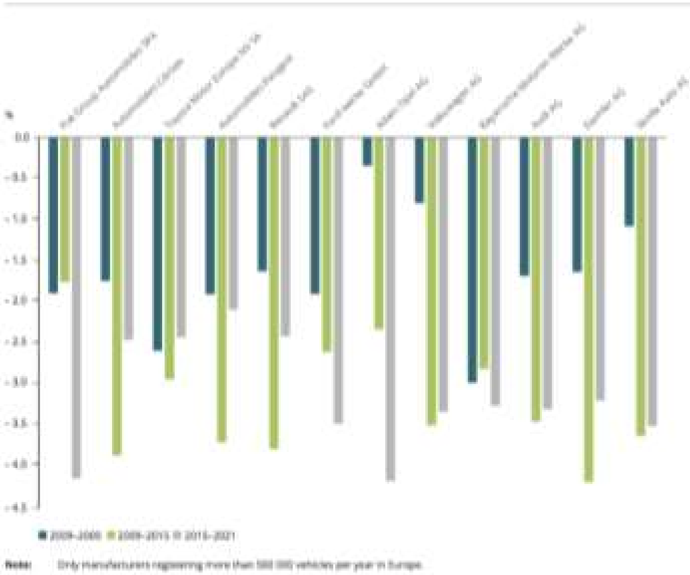


Figure 79: Comparison of past and future progress towards meeting the 2021 target

Source: European Environment Agency Report

6.2 Penalties

If a manufacturer's or a pool's average specific CO2 emissions exceed the specific emission target, Regulation (EC) No 443/2009 requires the payment of an excess emission premium. This premium is calculated by multiplying the following three elements:

• the distance to the emission target in a given year (in g CO2/km), i.e. the excess emissions.
• the number of vehicles registered by the manufacturer during that year.
• the premium level included in Table 3.9.

The premium amounts to 5€ for the first gram of CO2/km of exceedance, 15€ for the second, 25€ for the third and 95€ for each subsequent gram.
A higher distance to the target therefore implies a higher excess premium per gram of CO2/km emitted.

Excess emissions ($g\ CO_2/km$)	Fine (EUR)				Number of vehicles	Formula for calculating excess emission premium (EUR)
	5	15	25	95		
0–1	(EE)	-	-	-	NV	((EE) * 5)*NV
1–2	1	(EE — 1)	-	-	NV	(1*5 + (EE-1)*15)*NV
2–3	1	1	(EE — 2)	-	NV	(1*5 + 1*15 + (EE-2)*25)*NV
> 3	1	1	1	(EE — 3)	NV	(1*5 + 1*15 + 1*25 + (EE-3)*95)*NV

Note: EE, distance to target or excess emission; NV, number of vehicles registered.

Table 19: Coefficients to be used in the formula for calculating excess emissions premium

For example, if a manufacturer registers 100 000 vehicles in the EU, the formula to be used for calculating the excess emission premium varies depending on the distance to the target as follows:

• if the distance to the target is 0.5 g CO2/km, the first formula in Table 19 applies and the excess emission premium = 0.5 * 5 * 100 000 = EUR 250 000;
if the distance to the target is 1.5 g CO2/km, the second formula in Table 19 applies and the excess emission premium = (1 * 5 + (1.5 – 1) * 15) * 100 000 = EUR 1 250 000;

• if the distance to the target is 2.5 g CO2/km, the third formula in Table 19 applies and the excess emission premium = (1 * 5 + 1 * 15 + (2.5 – 2) * 25) * 100 000 = EUR 3 250 000;

• if the distance to the target is 3.5 g CO2/km,
the fourth formula in Table 19 applies and the excess emission premium =
(1 * 5 + 1 * 15 + 1 * 25 + (3.5 – 3) * 95) * 100 000 = EUR 9 250 000.

In 2015 only two manufacturers were required to pay the excess emission premium: Aston Martin Lagonda and Ferrari.

To further increase the improvements and to avoid manufacturers not to take it easy, European Commision has stated that from 2019 every g/km in excess will have a cost of 95€.
But the law also includes so-called super credits for low-emission cars. From 2013 to date, the "super credits" for vehicles with CO2 emissions <50 g/km in the calculation of the average will be counted as: 3.5 vehicles in 2012 and 2013, reduced to 2.5 in 2014, to 1.5 vehicles in 2015 and a vehicle from 2016 until 2019.
To promote the spread of electric cars and plug-in hybrids, the regulation allows super credits also from 2020 to 2022, but limited to 7.5 g / km. In particular, a low emission car will count as 2 cars in 2020, as 1.67 in 2021 and as 1.33 in 2022, to then be considered as all the others starting from 2023.

	Registration	Average CO_2 emissions ($g CO_2/km$)	Average mass (kg)	Average engine capacity (cm^3)
E85	1 704	142.7	1 480	1 794
Electric	56 756	0.0	1 588	-
LPG	138 065	120.0	1 220	1 329
NG-biomethane	78 278	98.9	1 287	1 183
Petrol-electric	89 364 ([b])	48.7	1 743	1 709
Diesel-electric	14 189 ([b])	74.8	1 605	1 966

Note: ([a]) Electric vehicles are vehicles for which tail-pipe emissions are 0 g CO_2/km.

([b]) Some countries reported hybrids as plug-in hybrids. The overestimate is around 10 %.

Only exhaust emissions are considered. For electric monofuel vehicles the emission is null. For E85, only the petrol CO_2 emissions are reported; for LPG and NG-biomethane the respective LPG and compressed NG CO_2 emissions are reported.

Table 20: AFV data: number or registrations, CO2 emissions, mass and engine capacity

7. DIESELGATE

7.1 The research

As in Europe, also in the USA, the emissions tests didn't prove too realistc when real number fgiures were compared to the ones of real life conditions.
This was one of the reasons that led the research team of the West Virginia University composed by Arvind Thiruvengadam and Hemanth Kappanna (both from India, from Chennai and Bangalore) and Marc Besch from Biel, Switzerland, to start a study concerning the measuring of emissions in real life conditions.

Figure 80: Researchers Arvind Thiruvengadam, Hemanth Kappanna and Marc Besch

Their final work, *In-Use Emissions Testing of Light-Duty Diesel Vehicles in the United States*, was only the first document that ignited the big fire of the biggest scandal of modern automotive industry. The findings were provided to the California Air Resources Board (CARB) in May 2014 and soon after all the lights were on the VW group.

The test was carreide out on 3 veichles, that in a first step were not explicitally named, but were easily inferrable from the data regarding them. The researcher only called them Veichles A, B and C:

"Vehicle A featured a lean NOx trap (LNT) for NOx abatement, whereas Vehicle B was fitted with an aqueous urea- based selective catalytic reduction system. Both vehicles had a DPF installed for controlling particulate matter emissions. Vehicle C was fitted with a 3.0L turbocharged in-line six-cylinder engine in conjunction with an aqueous urea-SCR system and DPF for NOx and PM control, respectively."

All three test vehicles were compliant with EPA Tier2-Bin5, as well as California LEV-II ULEV (for Vehicles A and B) and LEV-II LEV (for Vehicle C) emissions standards as per EPA certification documents. Vehicles A and B are categorized as 'light-duty vehicles' (LDV) whereas Vehicle C as 'light-duty truck 4' (LDT4). The 3 veichles were in order, 2 Volkswagen and 1 BMW (VW Passat, VW Jetta equipped with a 2.0 TDI 140 HP engine and a BMW X5 equipped with a 3.0d 270 Hp engine). The choice was driven by the importance of VW in the widespread of Diesel engines in the USA. The group had put a big effort in advertising their diesel cars as the greenest and most ecological on the market, winning coinjointly the award for green car of the year for the VW Jetta and Audi A3.

GREEN CAR OF THE YEAR (USA)

2009 — Volkswagen Jetta TDI Clean Diesel*
2010 — Audi A3 TDI Clean Diesel.*
2011 — Chevrolet Volt plug-in hybrid.
2012 — Honda Civic GX natural gas vehicle.
2013 — Ford Fusion second generation line-up, including the EcoBoost gasoline engine option, and the Fusion hybrid and plug-in variants.
2014 — Honda Accord ninth generation line-up, including gasoline, hybrid, and plug-in hybrid variants.
2015 — BMW i3.
2016 — Second generation Chevrolet Volt.
2017 — Chevrolet Bolt EV.

*following the Dieselgate scandal and the VW admission of guilt, both awards were rescinded.

Vehicle		A	B	C
Mileage at test start [miles]		4,710	15,226	15,031
Fuel		ULSD	ULSD	ULSD
Engine displacement [L]		2.0	2.0	3.0
Engine aspiration		Turbocharged/ Intercooled	Turbocharged/ Intercooled	Turbocharged/ Intercooled
Max. engine power [kW]		104 @ 4200 rpm	104 @ 4200 rpm	198
Max. engine torque [Nm]		320 @ 1750 rpm	320 @ 1750 rpm	-
Emission after-treatment technology		OC, DPF, LNT	OC, DPF, urea-SCR	OC, DPF, urea-SCR
Drive train		2-wheel drive, front	2-wheel drive, front	4-wheel drive
Applicable emissions limit	*U.S. EPA*	T2B5 (LDV)	T2B5 (LDV)	T2B5 (LDV)
	CARB	LEV-II ULEV	LEV-II ULEV	LEV-II LEV
EPA Fuel Economy Values [mpg] [1)]	*City*	29	30	19
	Highway	39	40	26
	Combined	33	34	22
EPA CO_2 Values [g/km] [1)]		193	186	288

[1)] *EPA advertised fuel economy and CO_2 emissions values for new vehicles in the US (www.fueleconomy.gov)*

Figure 81: Test vehicles and engine specifications

Car A: Volkswagen Jetta

Car B: Volkswagen Passat

Car C: BMW X5

Figure 82: Cars tested

The cars went for five test spins in and around three California cities:

- Route 1: Some 43 miles of weekday, non-rush hour highway driving in Los Angeles, at average speeds of 48 mph.
- Route 2: More than 15 miles of weekday driving in downtown L.A., at average speeds of 15 mph.
- Route 3: Nearly 37 miles of rural up and down driving in the L.A. foothills, at 32 mph.
- Route 4: A trip through downtown San Diego, similar in length and speed to Route 2.
- Route 5: A trip through downtown San Francisco.

The cars were warmed up before each test, which is important because it's normal for a vehicle to spew higher NOx emissions when the engine first gets going. They were also relatively new, none exceeding 16,000 miles, meaning there's no reason to think the emissions filters would have deteriorated from age.

The main issue met during the set-up phase was the way to actually measure emissions in a real drive situation. The difficulties concerned all the machineries needed to compute data and their space and power supplies needed on board of the car:
For on-road testing with both Vehicles A and B, a 2kW Honda gasoline fuelled generator was utilized to supply the necessary electrical power to operate the OBS, PPS and ancillary systems. The power requirements for the OBS- TRPM however, required the addition of a second 2kW Honda generator to support the power demand for the entire sampling setup during testing of Vehicle C. Using a vehicle independent power generator had the advantage of not having to draw any current from the test vehicles power system; hence, no additional load was added to the engine which might have skewed the emissions production rate and therefore the results of this study.
It has to be noted that the addition of measurement equipment was increasing the actual vehicle weight, thereby possibly influencing the engine's load demand and resulting emissions rates. The payload of Vehicles A and B was representative of four adult passengers totalling 300kg when assuming 75kg per individual passenger (i.e. Vehicle A: 305kg, Vehicle B: 314kg), whereas Vehicle C's payload had to account for additional 230kg (i.e. 533kg).

Looking at the following images, is easily inferable how complicated can result the measurement of real-driving condition's emissions, a tool that asks for customisation for every car.

Figure 83: Instrument Set-Up of VW Jetta: Exhaust adapter setup for Vehicle A, left: flexible high temperature exhaust hose connecting double vehicle exhaust tip to exhaust transfer pipe, right: 2" exhaust flow meter (EFM)

Figure 84: Instrument Set-Up of VW Passat: Exhaust adapter setup for Vehicle B, left: flexible high temperature exhaust hose connecting single vehicle exhaust tip to exhaust transfer pipe, right: 2” exhaust flow meter (EFM)

Figure 85: Instrument Set-Up of BMW X5: Exhaust adapter setup for Vehicle C, left: 3.5” exhaust flow meter (EFM), right: joining double vehicle exhaust stack into exhaust transfer pipe

7.2 Results

In the presentation of the final results, the researchers first showed what were the emission limits under which the veichles had to undergo.

NO_x [g/km]	CO [g/km]	THC [g/km]	CO_2 [g/km]	PM [g/km]	PN [#/km]
0.043	2.610	0.056	193 (*Vehicle A*) 186 (*Vehicle B*) 288 (*Vehicle C*)	0.006	$6.0x10^{11}$

Table 21: Applicable regulatory emissions limits and other relevant vehicle emission reference values: US-EPA Tier2-Bin5 at full useful life (10years/120.000 mi for NOx, CO, THC and PM

The following table is the most controversial results that soon after led to deeper research about NOx emission.

As can be easily seen, the NOx emission of the two VW are far above the green dotted line that represent the actual limit of Tier2-Standard. VW failed spectacularly: NOx emissions for “Vehicle A” (the Jetta) were 15 to 35 times higher than the EPA standards, and those for “Vehicle B” (the Passat) were 5 to 20 times higher. The BMW instead passed the test, though its NOx emissions did creep up a bit during hilly driving.

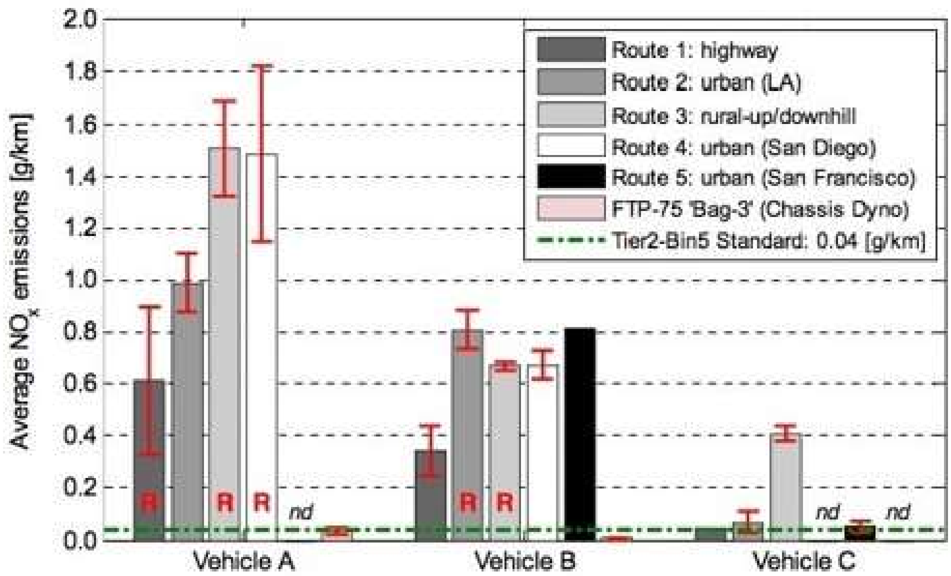


Figure 86 Average NOx emissions of test vehicles over the five test routes compared to US-EPA Tier2-Bin5 emissions standard

In detail the following charts show how in fact, Volkswagens never undergo the actual limits of NOx, in none of the different driving test conditions.

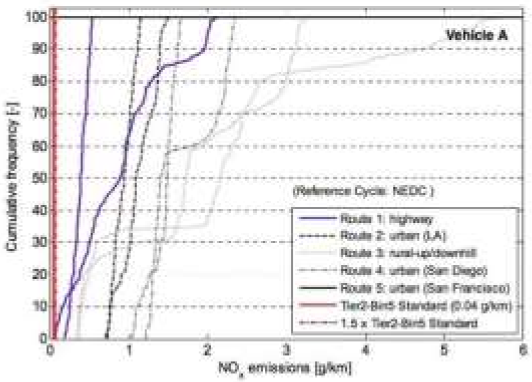


Figure 87: Averaging window NOx, emissions for vehicle A over the five test routes compared to US-EPA Tier2-Bin5 emissions standard.

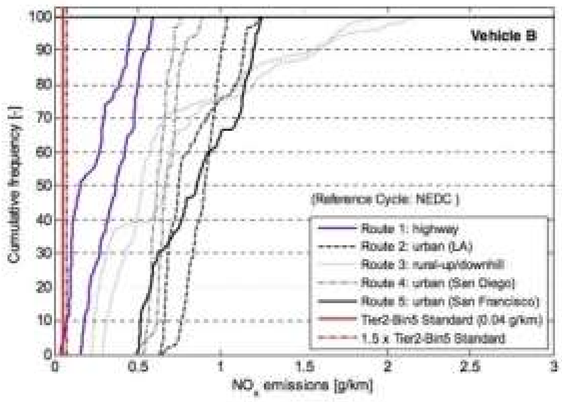


Figure 88. Averaging window NOx, emissions for vehicle B over the five test routes compared to US-EPA Tier2-Bin5 emissions standard.

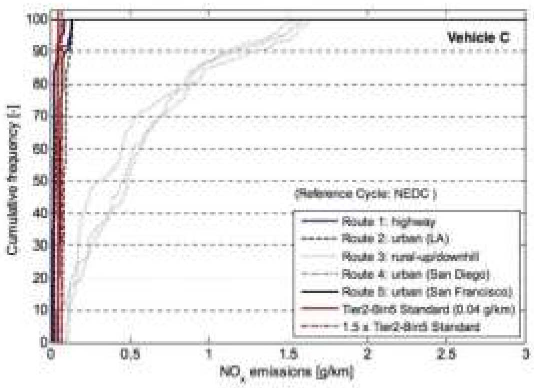


Figure 89: Averaging window NOx, emissions for vehicle C over the five test routes compared to US-EPA Tier2-Bin5 emissions standard.

"The summary, real-world NOx emissions were found to exceed the US-EPA Tier2-Bin5 standard by a factor of 15 to 35 for the LNT equipped Vehicle A, by a factor of 5 to 20 for the urea-SCR fitted Vehicle B (same engine as Vehicle A) and at or below the standard for Vehicle C with exception of rural-up/downhill driving conditions, over five pre- defined test routes.
Generally, distance-specific NOx emissions were observed to be highest for rural-up/downhill and lowest for high-speed highway driving conditions with relatively flat terrain. <u>Interestingly, NOx emissions factors for Vehicles A and B were below the US-EPA Tier2- Bin5 standard for the weighted average over the FTP-75 cycle during chassis dynamometer testing.</u>

NOx emissions of Vehicle B over the cross-multi state driving route, comprising predominantly highway driving, were observed to be approximately 6 times exceeding the US-EPA Tier2-Bin5 standard. However, most interestingly NOx emissions were found to be below the regulatory standard for portions of the route characterized by low or negligible changes in altitude and with the vehicle operated in cruise-control mode at approximately 120km/h."

Concerning the other pollutants, the results were the following:

In general, CO and THC emissions were observed to be well below the regulatory level for all three test vehicles and driving conditions, with exception of Routes 1 and 2 for Vehicle A where THC emissions were seen to exceed the regulatory level by a factor of 1.25.

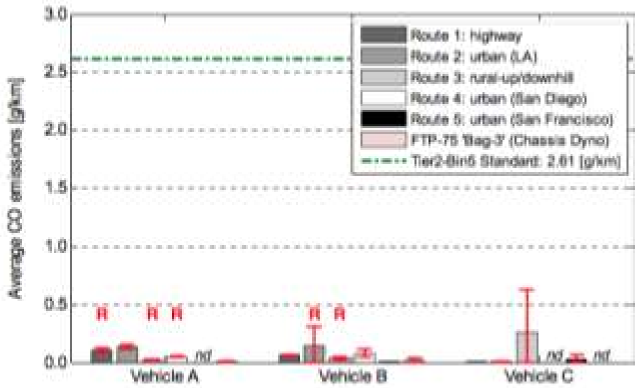


Figure 90: Average CO emissions of test vehicles over the five test routes compared to US-EPA Tier2-Bin5 emission standard.

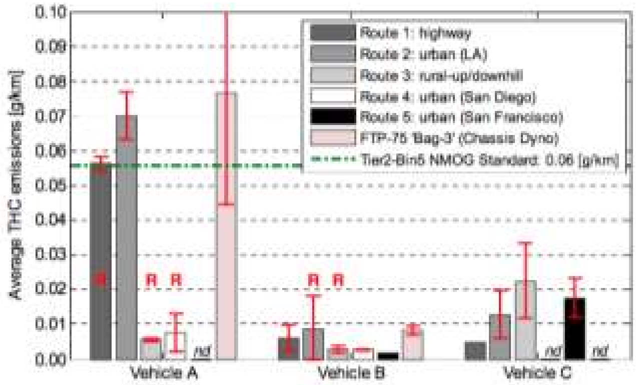


Figure 91: Average THC emissions of test vehicles over the five test routes compared to US-EPA Tier2-Bin5 emission standard.

Highway driving showed lowest CO2, whereas urban/suburban driving conditions lead to highest CO2 emissions factors for all vehicles. Since both Vehicles A and B were equipped with the same engine and similar test weights (1855kg vs. 1884kg), comparable CO2 consumption patterns were observed in agreement with results obtained during chassis dynamometer testing over the NEDC for urban/suburban and highway driving portions. It has to be noted that the actual weights of the cars were increased by the emissions' measurement devices by a factor between 8% and 14%.

Average fuel economy for highway driving with Vehicles A and B was 45.3 mpg and 43.7mpg, respectively, and 27.3 mpg for Vehicle C which is ~39% lower compared to Vehicles A and B. On the other hand, urban/suburban driving results in average fuel economies of 30.0mpg and 26.6 mpg for Vehicles A and B, respectively, and 18.5mpg for Vehicle C which is 35% lower compared to Vehicles A and B. Overall, urban/suburban driving leads to a 32-39% reduction in fuel economy over highway driving.

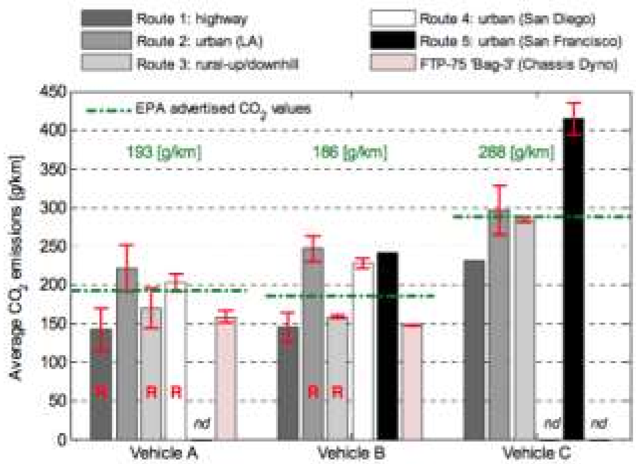


Figure 92: Average CO2 emissions of test vehicles over the five test routes compared to EPA advertised CO2 values for each vehicle.

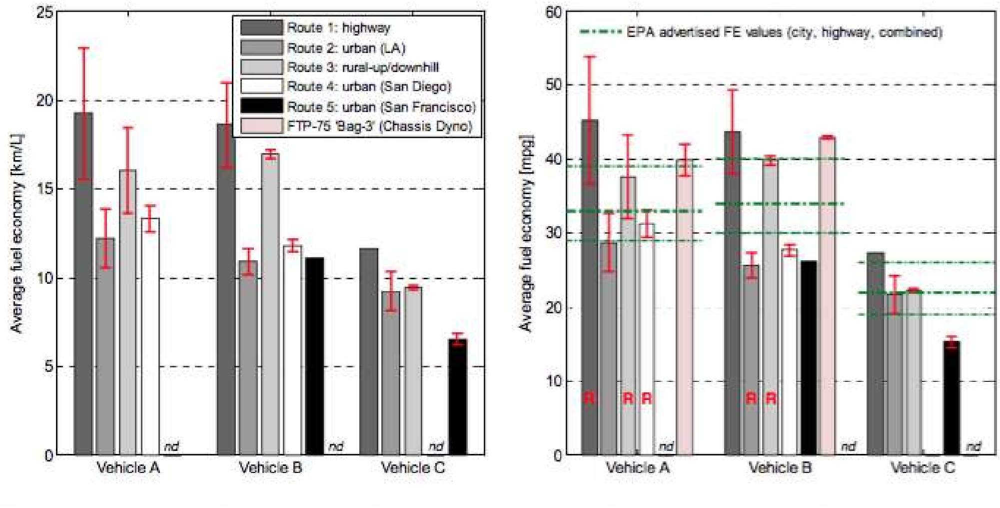


Figure 93. Average fuel economy of test vehicles over the five test routes in KM/L and mpg.

Particulate matter mass emissions, inferred from PPS measurements, were observed below the US-EPA Tier2-Bin5 standard for Vehicles A and B. On the other hand, particulate number emissions were found to exceed the Euro 5b/b+ PN standard during DPF regeneration events increasing by 2 to 3 orders of magnitude over emissions levels measured during none-regeneration events. It is noted that PN is not regulated in the United States.

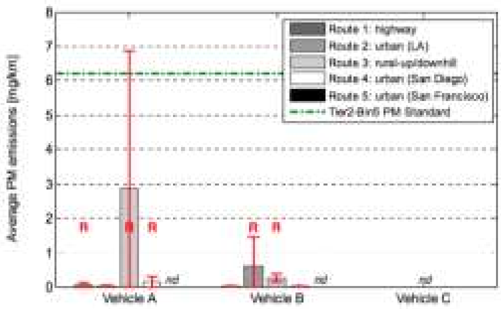


Figure 94: Average Pm emissions of test vehicles over the five test routes compared to USA-EPA Tier2-Bin5 emission standards.

7.3 Conclusions

On their own, the high NOx levels of the VW models might have warranted some fines or negative attention for the company. <u>But it was the comparison of NOx produced during road tests with the levels found during lab tests that attracted the attention towards VW's defeat device.</u>

The lab tests, when those devices effectively told the cars to behave, produced NOx emissions 50 and 64 percent below EPA regulations for Vehicle (the Jetta) A and Vehicle B (the Passat), respectively. Those findings are shown in the chart below as FTP-75:

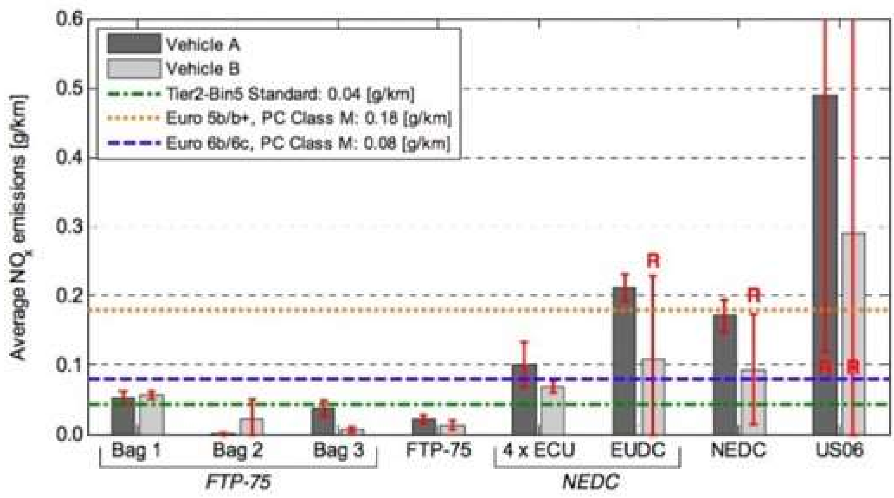


Figure 95: Average NOx emissions of test vehicles A and B over three standard chassis dynamometer test cycles (FTP-75, NEDC, and US06) compared to US-EPA Tier2-Bin5, Euro5b/b+ and Euro6b/6c emission standards.

This big difference only in the NOx emission attracted the attention of the United States Environmental Protection Agency that soon spoke officially: “The West Virginia University study raised questions about emissions levels from light-duty diesel Volkswagen vehicles during on-the-road testing”.

The researchers of the University stated that both Vehicles A and B were operating as intended and did not have any malfunctions, making clear that the differences on the result were a praxis for VWs.

In the following months further research were carried on and soon was clear that this anomalous behaviour of the Volkswagen group car was due to a software specification, designed to recognize the test situation and to change the ECU Mapping.

The research was published in May 2014 and handed it over to the Environment Protection Agency (EPA). There was an expectation that they would find out what was causing the higher-than-expected emissions, they did send a courtesy copy to VW to say ‘vehicles A and B are your vehicles and you might like to know’ but there was no response.

There was no response from the EPA either, but it was noticed an EPA press release in which VW agreed to recall almost 500,000 vehicles in December 2014 to reinstall software, which it said would solve the higher-than-expected emissions.

However, a couple of months later the California Air Resources Board (Carb) carried out spot checks and discovered that the "defeat device" software – used to dramatically reduces nitrogen oxide emissions only when the cars are undergoing strict emission tests – was still present.

"That is actually the single most inexplicable thing about this whole business," John German, one of the engineers enveloped in the research said*. "VW had a chance to fix the problem, and they continued to try and cheat and do what they had done. That's just amazing.*

According to the EPA, Volkswagen had insisted for a year before the outbreak of the scandal that discrepancies were mere technical glitches. Volkswagen only fully acknowledged that they had manipulated the vehicle emission tests after being confronted with evidence regarding the "defeat device".
Only then did **VW admit it had designed and installed a defeat device in these vehicles in the form of a sophisticated software algorithm that detected when a vehicle was undergoing emissions testing**," the EPA said in a statement last week.

7.4 Defeat Device

On Friday, September 18, 2015, the United States Environmental Protection Agency, or EPA, announced that the automaker Volkswagen has illegally installed manipulation software designed to circumvent environmental regulations on NOx emissions and diesel pollution; under normal driving conditions, passenger cars would have exceeded the limit allowed by law as far as 40 times.

The software sensed when the car was being tested and then activated equipment that reduced emissions, United States officials said. But the software turned the equipment down during regular driving, increasing emissions far above legal limits, most likely to save fuel or to improve the car's torque and acceleration.
The software was modified to adjust components such as catalytic converters or valves used to recycle some of the exhaust gasses. The aim was clear: to pass the homologation tests while providing customers with cars able to deliver good performances and lower consumption overall.
The defeat device is a specially written engine management unit firmware that detects the position of the steering wheel, vehicle speed, the duration of the engine's operation, and barometric pressure when positioned on a dynamometer using the FTP-75 test schedule.

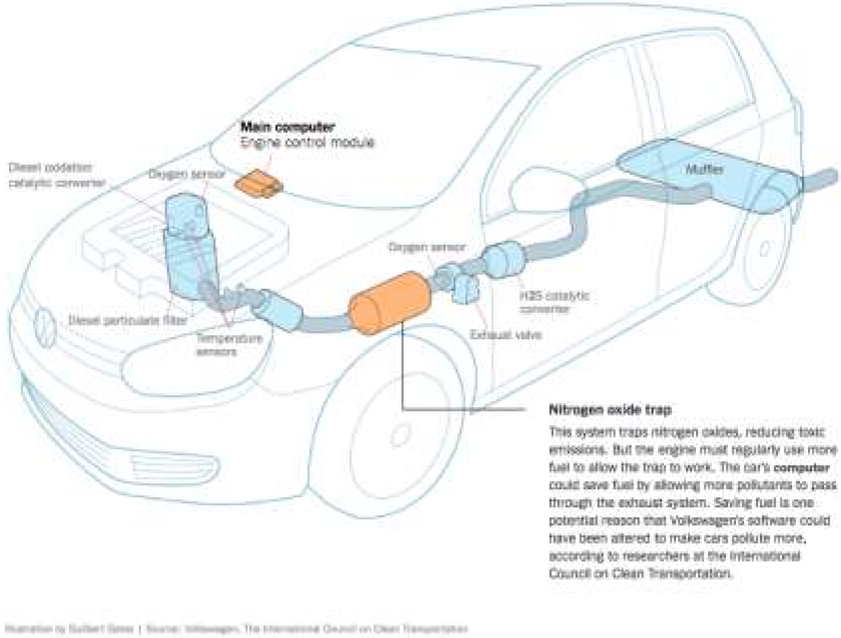


Figure 96: VW Defeat Device scheme

In September 2015 the Environmental Protection Agency ordered Volkswagen to recall seven of its American car models equipped with 2-litre TDI engines, and sold in the US between 2009 and 2015, which amount to nearly 600,000 vehicles. The vast majority of the other affected cars, about 8.5 million, are in Europe and include Skoda and Seat cars not sold in the United States. The rest of the vehicles are scattered around Asia, Africa and South America, where diesels account for a relatively small percentage of cars sold.

Figure 97: VW models under accuse

The E.P.A. said on November 2015 that it had found the same test-cheating software on additional Volkswagen and Audi diesel models and on a Porsche model. The agency said it covered about 10,000 cars sold in the United States since the 2014 model year. But in meetings with the E.P.A., the company admitted that all model years since 2009 with its 3-liter diesel engines contained the software as well. The latest disclosure covers an additional 80,000 vehicles.

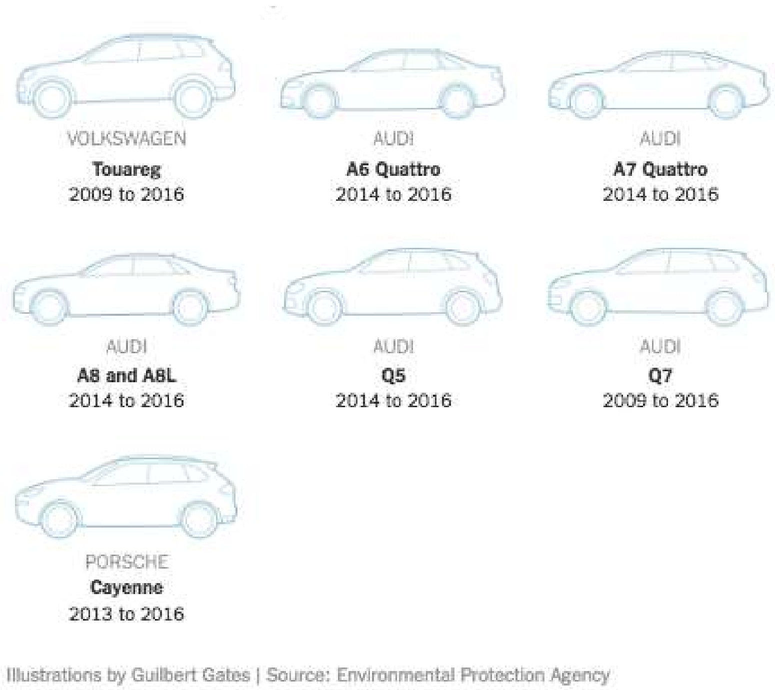


Figure 98: Audi models under accuse

On 3 November 2015, VW revealed that its internal investigation found that CO2 emissions and fuel consumption figures were also affected by "irregularities". These new issues, first estimated to cost up to €2 billion to repair, involved mainly diesel, but also some petrol models, with initial estimates suggesting that approximately 800,000 vehicles equipped with 1.4, 1.6 and 2.0 litre motors from VW, Skoda, Audi and Seat might be affected. On 9 December 2015, VW revised these estimates, saying that only around 36,000 vehicles are affected by the irregularities, while also affirming that it had found no evidence of unlawful changing of CO2 emissions data.
In November 2016, California regulators nevertheless claimed to have discovered software installed on some Audi models that allowed the manufacturer to cheat CO2 emissions during standard testing, thereby also masking the cars' contribution to global warming.

7.4 Consequences

7.4.1 USA

On 4 January 2016, the Justice Department, on behalf of the EPA, filed a lawsuit against VW in a federal court in Detroit. The complaint, seeking up to $46 billion in penalties for Clean Air Act violations, alleges that VW equipped certain 2.0 and 3.0 litre diesel-engine vehicles with emissions cheating software, causing NOx pollution to exceed EPA's standards during normal driving conditions. The suit further claimed that "efforts to learn the truth about the (excess) emissions … were impeded and obstructed by material omissions and misleading information provided by VW entities", while "so far recall discussions with the company have not produced an acceptable way forward".

On 29 March 2016, Volkswagen was additionally sued by the United States Federal Trade Commission for false advertising due to fraudulent claims made by the company in its promotion of the affected models, which touted the "environmental and economic advantages" of diesel engines and contained claims of low emissions output. The suit was consolidated into existing litigation over the matter in San Francisco, which would allow the FTC to participate in global settlements over the matter.
The *Los Angeles Times* reported that the number of class-action lawsuits filed by privates had grown to more than 230.

On 28 June 2016, Volkswagen agreed to pay $15.3 billion to settle the various public and private civil actions in the United States, the largest settlement ever of an automobile-related consumer class action in United States history. On 25 October 2016, a U.S. federal judge approved the settlement.

On 9 September 2016, James Robert Liang, a VW engineer working at VW's testing facility in Oxnard, California, admitted as part of a plea deal with the US Department of Justice that the defeat device had been purposely installed in US vehicles with the knowledge of his engineering team: "Liang admitted that beginning in about 2006, he and his co-conspirators started to design a new "EA 189" diesel engine for sale in the United States. When he and his co-conspirators realized that they could not design a diesel engine that would meet the stricter US emissions standards, they designed and implemented the defeat device software".

On 25 October 2016, a final settlement was approved by a judge. About 475,000 Volkswagen owners in the US can choose between a buyback or a free fix and compensation, if a repair becomes available. Up to $10 billion will be paid to VW or Audi owners whose cars are equipped with 2.0 litre diesel engines. Owners can also opt to have their car repaired free of charge or can sell it back to the company, who will pay back its estimated value from before the scandal began.

Leases can also be terminated without incurring penalty charges. Independent of which options are selected, owners will still receive compensation ranging from $5,000 to $10,000 per affected car. Additionally, should they choose to decline the offer, they are free to pursue independent legal action against the firm. The settlement also includes $2.7 billion for environmental mitigation, $2 billion to promote zero-emissions vehicles and $603 million for claims by 44 states, Washington, D.C., and Puerto Rico. VW agreed not to resell or export any vehicles it repurchases unless an approved emission repair has been completed. As of 28 June 2016, no practical engineering solutions that would bring the vehicles into compliance with emission standards had been publicly identified.
VW will begin administering the settlement immediately, having already devoted several hundred employees to handling the process. Buybacks range in value from $12,475 to $44,176, including restitution payments, and vary based on mileage. People who opt for a fix approved by the Environmental Protection Agency will receive pay-outs ranging from $5,100 to $9,852, depending on the book value of their car.
Of the buyback, 138,000 had been completed by 18 February 2017 with 150,000 more to be returned. 52,000 chose to keep their cars. 67,000 diesel cars from model year 2015 are cleared for repairs. The situation is unclear for the more difficultly repairable 325,000 "Generation One" diesel VWs from the 2009-2014 model years, which use the "lean NOx trap".

On 7 January 2017, a former top emissions compliance manager for Volkswagen in the US was arrested by the FBI on a charge of conspiracy to defraud the United States. On 11 January 2017 VW pleaded guilty to weaving a vast conspiracy to defraud the US government and obstructing a federal investigation and agreed to pay a US$2.8 billion criminal fine and US$1.5 billion in civil penalties. In addition, six executives have been criminally charged.

A settlement with US authorities requires Volkswagen to install electric vehicle infrastructure, available to all electric cars. VW plans hundreds of chargers with 50, 150 and 320 kW charge rate, beginning in California in 2017. Competing charge networks (and automakers) view the effort as controversial.

Cars from the buyback program have been stored at various regional US staging sites: Colorado Springs, Colorado; Pontiac, Michigan; Baltimore, Maryland; and San Bernardino, California, as in the example of Figure 99.

Figure 99: Thousands of Volkswagen diesel vehicles are parked at the vacant Pontiac Silverdome. VW bought back the cars back from their owner

7.4.2 People involved and formal accusations

Figure 100: Martin Winterkorn

In September 2015, Martin Winterkorn, former VW CEO, apologized for Volkswagen AG having installed software in its diesel cars to allow the vehicles to pass emissions tests by decreasing emissions when the vehicle detected it was undergoing testing but otherwise pollute at amounts well beyond legally allowed limits. Winterkorn confirmed that Volkswagen AG could face fines of up to $18bn, but had not issued a recall at the time of Winterkorn's departure. He blamed "the terrible mistakes of a few people," whom he did not name, for the international scandal. Winterkorn resigned as CEO on 23 September 2015, as he accepted responsibility for the scandal while asserting that he was "not aware of any wrongdoing on my part."

He additionally resigned as Audi chairman on November 11, 2015. The resignation came a week after additional revelations were made public regarding further vehicle emission test rigging, this time in gasoline-powered vehicles, in amounts approaching one million.

In the U.S., six current and former Volkswagen managers have been charged:

- Heinz-Jakob Neusser: from July 2013 until September 2015, Neusser worked for VW as head of Development for VW Brand and was also on the management board for VW Brand.
- Jens Hadler: from May 2007 until March 2011, Hadler worked for VW as head of Engine Development for VW.
- Richard Dorenkamp: from 2003 until December 2013, Dorenkamp worked for VW as the head of VW's Engine Development After-Treatment Department in Wolfsburg, Germany.
- Bernd Gottweis: from 2007 until October 2014, Gottweis worked for VW as a supervisor with responsibility for Quality Management and Product Safety.
- Oliver Schmidt: from 2012 through February 2015, Schmidt was the General Manager in charge of the Environment and Engineering Office, located in Auburn Hills, Michigan.
- Jürgen Peter: Peter worked in the VW Quality Management and Product Safety Group from 1990 until the present. From March 2015 until July 2015, Peter was one of the VW liaisons between the regulatory agencies and VW.

Oliver Schmidt, the first manager of Volkswagen arrested official diesel, was sentenced to 7 years in prison, which cut the eleven months of preventive detention of $100,000 fine. Before Schmidt, the same judge Sean Cox had already inflicted 3 years and 4 months on the Indonesian engineer James Liang. In both cases the maximum penalty was applied: $400.000 for Schmidt and $200,000 for Liang, whose lawyer had immediately announced an appeal. Liang was the key witness and was cooperating with the investigators.

Figure 101: Oliver Schmidt

A former Italian engineer of Audi, Giovanni Zaccheo Pamio, has been in prison in Germany for months. The request for extradition overseas is hanging on his head. Wolfgang Hatz, formerly Chief Engine Engineer of Audi before being promoted to head of Porsche's Research & Development, is also in custody on the orders of the Munich Public Prosecutor's Office.

The prosecution in Braunschweig near Wolfsburg is investigating 21 suspects for fraud, but it is taking its own time. The prosecutors might not come to a decision in 2017, spokesman Klaus

Ziehe told Reuters. “The Americans are a year ahead of us,” Ziehe said. Reuters received hints that no board members are among the suspects.

Johannes Thammer, managing director of Audi Volkswagen Korea, was placed under investigation and faces up to five years in prison and a fine of up to ₩30,000,000.

7.4.3 Outside USA

A Canadian settlement, which keeps to terms that are comparable to the U.S. settlement finalized in October, will cover about 105,000 vehicles there and potentially cost the automaker the equivalent of U.S. $1.6 billion. As in the United States, Canadian owners will be eligible to sell their vehicle back at an agreed-upon price or opt to fix their vehicle and receive a payment. And under a tentative consumer settlement in Canada, Volkswagen and Audi Canada will pay out the equivalent of U.S. $11.2 million.

Government regulatory agencies and investigators have initiated proceedings in France, Italy, Germany, Switzerland, Spain, the Netherlands, the Czech Republic and Romania. Several countries have called for a Europe-wide investigation.
On 27 October 2015, the European Parliament voted a resolution urging the bloc to establish a federal authority to oversee car-emissions, following reports in the press that top EU environmental officials had warned, since early 2013, that manufacturers are tweaking vehicles to perform better in the lab than on the road.

In June 2016 documents leaked to the press indicated that European Commission officials had been warned in 2010 by their in-house science team that at least one car manufacturer was possibly using a NOx-related defeat device in order to bypass emission regulation. Kathleen Van Brempt, the chair of the EU inquiry into the scandal, found the documents "shocking" and suggested that they raised serious concerns with regard to the future of commission officials: "These documents show that there has been an astonishing collective blindness to the defeat device issue in the European commission, as well as in other EU institutions".

German prosecutors have launched an investigation against former Volkswagen chief executive Martin Winterkorn. Winterkorn had resigned over the scandal, saying he had no knowledge of the manipulation of emissions results.

Police raided VW headquarters on 8 October 2015. On 16 October 2015 there were 20 investigators working on the case, targeting "more than two, but a lot fewer than 10" VW staff. The KBA was testing 50 cars from different manufacturers in November 2015, both in laboratory and on-road with PEMS. In May 2016, German transport minister Alexander Dobrindt said that

Volkswagen, Audi, Mercedes-Benz, Opel and Porsche would all adjust settings that increased emission levels such as nitrogen dioxide in some diesel cars. On 16 March 2017, German authorities raided the headquarters of Audi in Bavaria and Volkswagen in Wolfsburg.

Italy's competition regulator announced plans to investigate whether VW engaged in "improper commercial practices" when promoting its affected diesel vehicles.
On 15 October 2015, Italian police raided VW offices in Verona, and the company's Lamborghini offices in Bologna, placing six executives under investigation.
In Italy a big class action is being carried out by Altroconsumo, representing more than 90.000 customers that sued VW. The amount of the requests could cost to the company 400 million of Euros.

Almost every country in the world were VW sold its diesel equipped cars, started a penal process towards the company. The total cost for the company was estimated to a total of 30 Billions $.

7.5 Effects

- **Stock Value**

On 21 September 2015 the first day of trading after the EPA's Notice of Violation to Volkswagen became public, share prices of Volkswagen AG fell 20% on the Frankfurt Stock Exchange. On 22 September, the stock fell another 12%. On 23 September, the stock quickly fell 10.5%, dropping below €100 to a record 4-year low before regaining some lost ground. Share prices of other German automakers were also affected, with BMW down 4.9% and Daimler down 5.8%. A year later VW stock was down by 30%. Qatar, one of the biggest VW shareholders with a 17% stake in the company, lost nearly $5 billion as the company stock value fell.

- **Sales**

The US sales of Volkswagens was 23,882 vehicles in November 2015, a 24.7% decline from November 2014.
As far as 2017, VW has started to gain back some market share through massive investments, advertising and new models. Audi instead has never suffered noticeably, the Dieselgate has only slowed down a bit a constant increase in sales.

YEAR	Volkswagen All models	Market Share	Audi All Models	Market Share
2017	339.676	1,97%	226.511	1,30%
2016	322.948	1,84%	210.213	1,19%
2015	349.440	2,00%	202.202	1,16%
2014	366.970	2,22%	182.011	1,10%

Table 22: sales of VW and Audi in the USA 2014-2017

In South Korea, sales in November rose 66% to 4,517 units from a year ago due to the Volkswagen's aggressive marketing efforts such as a discount of up to ₩18,000,000 (US $15,600 at December 2015 exchange rates) for some models.
In Great Britain, the scandal did not affecteed sales, which increased in 2016 to an all-point high, placing VW second in the league of best-selling cars. VW sales across Europe returned to growth in April 2016 for the first time since the scandal broke, with a group market share of 25.2%, compared to its previous level of 26.1%.

7.6 Image Damage

Soon after the news became of public interest, all the major news providers in USA but also Europe started talking about it, mining the image of VW, that was launched to overpass Toyota as the world leader of automotive industry.

Figure 102: Example of mocking images as a consequences of VW Dieselgate

The biggest damage to the whole VW Group was first of all of images, since the big economies of the group were enough to sustain the abnormal cost of the scandal without affecting dramatically the future of the company.

Most of the investments in the previous years concerned marketing and the building of an image of the most technological and advanced cars in the world. Above all for the Audi brand, that is the major source of income for the group. Big efforts were done to try to avoid connecting the "VW Dieselgate" to Audi brand, as well as Porsche, Seat and Skoda.

There were also accusations of behaviours not exactly fair of VW towards some newspaper, in order to try to minimize as much as possible the exposure of its Diesel in Europe.
The first case concerns an article in the French newspaper "Le Canard enchaîné" which published a letter sent by VW to the French press on 30 September. The gist of the speech is that in exchange for silence on each other, the already planned Audi advertising would continue, and the check for over 1,400,000 € cashed. VW denied all the accusations.


Le chantage de Volkswagen pour faire taire la presse française

-> Si nous pouvons assurer **formellement** à l'agence et à la marque que lors des dates de parutions **des 6, 8 et 10 octobre prochain**, il n'y aura aucun article relatif à la crise VW, nous conserverons les investissements ... soit 315 K€

-> Si pas possible de tenir cet engagement, nous serons dans l'obligation d'annuler ce dispositif.

Figure 103: Denunciation Post of Le Canard enchaine towards VW group

A similar accusation came from the newspaper Libero, which in an article announced that it has not stretched the hand to VW and have paid the consequences, through the withdrawal of the Audi advertising campaign. Also in this case the company called itself out of the accusations.

The sales data in Table 22, show that overall the biggest damage to the image of the company took place in the USA, a country that is far more sensible to this kind of events. VWs has never had a strong and solid image in the USA as it has in Europe, where is regarded as one of the top quality manufacturers.
As a proof here's some data of surveys carried on in both Germany and USA, showing how two different cultures can react differently to the same episode.

- Despite the scandal, one poll conducted for Bild suggested that the majority of Germans (55%) still have "great faith" in Volkswagen, with over three-quarters believing that other carmakers are equally guilty of manipulation. Similarly, a poll conducted by the management consultancy Prophet in October 2015 indicated that two-thirds of Germans believe the scandal to be exaggerated and continue to regard VW as a builder of "excellent cars".

- A survey by Northwestern University's Kellogg School of Management, Brand Imperatives and Survata said that nearly 50% of US consumers had either a positive or very positive impression of Volkswagen, while 7.5% had a "very negative" impression. Another US survey by market researcher AutoPacific found that 64% of vehicle owners do not trust Volkswagen and only 25% of them have a positive view of Volkswagen following the scandal.

7.7 January 2018 – Animals Test Scandal

New details about Dieselgate emerged in late January 2018, when an article published by "The New York Times" pointed out:

"In 2014, as evidence mounted about the harmful effects of diesel exhaust on human health, scientists in an Albuquerque laboratory conducted an unusual experiment: Ten monkeys squatted in airtight chambers, watching cartoons for entertainment as they inhaled fumes from a diesel Volkswagen Beetle.

German automakers had financed the experiment in an attempt to prove that diesel vehicles with the latest technology were cleaner than the smoky models of old. But the American scientists conducting the test were unaware of one critical fact: The Beetle provided by Volkswagen had been rigged to produce pollution levels that were far less harmful in the lab than they were on the road."

Legal proceedings and government records showed that Volkswagen, along with Daimler and BMW were also engaged in a prolonged, well-financed effort to produce academic research that they hoped would influence political debate and preserve tax privileges for diesel fuel.

The European Research Group on Environment and Health in the Transport Sector (E.U.G.T.), economically supported by Volkswagen, Daimler and BMW did not do any research itself. Rather, it hired scientists to conduct studies that might defend the use of diesel. It sponsored research that challenged everything from a World Health Organization decision in 2012, to classify diesel exhaust as a carcinogen to whether or not removing diesel-powered vehicles from cities would reduce pollution.

Daimler and BMW said they were unaware that the Volkswagen used in the Albuquerque monkey tests had been set up to produce false data.

In a statement, Daimler AG said “We are appalled by the extent of the studies and their implementation. We condemn the experiments in the strongest terms.” The company went on to say they are distancing “ourselves from the studies and the EUGT” and have “launched a comprehensive investigation into the matter.”

Volkswagen CEO Matthias Müller: “The methods practiced by EUGT were totally wrong. All this shows me yet again that we have to take ethical questions more seriously and sensitively. In our company and as an industry. There are things you just do not do.” Volkswagen added that it “explicitly distances itself from all forms of animal cruelty” as “animal testing contradicts our own ethical standards.” The automaker added “We are conscious of our social and corporate responsibilities and are taking the criticism regarding the study very seriously. We know that the scientific methods used by EUGT were wrong and apologize sincerely for this.”

Reuters reports that Volkswagen’s supervisory board has called for an investigation into who commissioned the tests. VW supervisory board Chairman Hans Dieter Poetsch also released a statement saying “Whoever is responsible for this must, of course, be held accountable.”

A number of environmental groups have already weighed in including Greenpeace’s Mel Evans who stated “*These bewilderingly abhorrent lab tests on monkeys and possibly humans, show yet again that VW is wholly untrustworthy and will do anything to promote dirty diesel*.”

7.8 Other Manufacturers.

Following VW, all the others manufacturers went under the spotlight, both in USA and Europe but also in Korea, another country that proved very sensitive about the topic.
The common thought, anyway, was that what VW did was not an "una tantum", but a common praxis of the automotive sector.
Thereby many others cars were tested with different outputs, leading to many official declarations and admission of guilt, as well as strong defences in the case of innocence.
Those are only some of the major cases that arose in the last years.

7.8.1 FCA

On May 2017, the Environmental Protection Agency accused Fiat Chrysler of installing software that enables certain diesel trucks to emit far more pollutants than emissions laws allow. The company denied those accusations, saying its software meets regulatory requirements.
The vehicles under spotlight were the 2014 to 2016 model year Dodge Ram 1500 pickup trucks and Jeep Grand Cherokees with 3.0-litre diesel engines. The allegations affect roughly 104,000 vehicles.
Janet McCabe, head of EPA's Office of Air and Radiation, said "no immediate actions are necessary" for owners because their vehicles are still safe and legal to drive.

Figure 104: Dodge RAM

The software reduced the amount of nitrogen oxide emitted during emissions tests, obscuring the fact that they spew more of the pollutant than is allowed under the Clean Air Act, officials said. They stopped short of calling the technology a "defeat device" (as in the case of VW), which is illegal, but said the company has not yet offered another explanation for the software.

Fiat Chrysler officials denied those claims in a statement. Every automaker must use “various strategies” to reduce tailpipe emissions without compromising the durability and performance of its engines, FCA said, adding that its emission control system complies with necessary requirements.
The company also said it has offered to make extensive changes to its software to address EPA concerns.

“FCA U.S. intends to work with the incoming administration to present its case and resolve this matter fairly and equitably and to assure the EPA and FCA U.S. customers that the company’s diesel-powered vehicles meet all applicable regulatory requirements,” the company said in a statement.

7.8.2 Renault

Major car manufacturers, including Renault issued press statements in 2015 reaffirming their vehicles' compliance with all regulations and legislation for the markets in which they operate.

Cars from several makers were tested in France, including Renault and Peugeot, whose headquarters were raided by fraud investigators in January and April 2016, respectively. Renault has subsequently recalled 15,000 cars for emission testing and fixing.

Renault has been under investigation by the Direction générale de la concurrence, de la consommation et de la répression des fraudes (DGCCRF) in France since 2015. Their report in 2017 states “the suspicion of the installation of a ‘fraudulent device’ which specifically modifies the functioning of the engine to reduce emissions of NOx (nitrogen oxides) in conditions specific to the regulatory tests.” It affects 900,000 vehicles, Renault Captur and Clio IV exceed the threshold for carbon dioxide emissions by 377% and 305%.

7.8.3 Mercedes

Searches were also carried out in several German Daimler sites for suspected manipulation on diesel models emissions. According to reports from the Stuttgart Prosecutor and the police in the Land of Baden-Wuerttemberg, 23 prosecutors and 230 policemen took part in the operation. 11 buildings searched in Baden-Wuerttemberg, Lower Saxony, Saxony and Berlin. In a note Daimler explained that he cooperated "completely" with the investigators. In March, the Stuttgart prosecutor's office had initiated an investigation.

Germany's Spiegel Magazin reported of a class action suit brought against Daimler AG, its CEO Dieter Zetsche, and its R&D chief Thomas Weber. The suit claims consumers were duped by Daimler's claim that its "BlueTec cars are the world's cleanest diesel.
The Daimler Group will recall over 3 million diesel-powered cars in Europe. This was announced by the German manufacturer: "The public debate on diesel is creating uncertainty especially in our customers" said the number one Dieter Zetsche "This is why we have decided additional measures to reassure the drivers of diesel cars". The intervention will cost the German group 220 million euros.

In February 2018, according to German paper "Bild am Sonntag", investigators found engine management function called "Slipguard", programmed to recognize whether the car was being tested in a laboratory.


Figure 105: Mercedes Bluetec diesel engine

Citing official documents, the paper also claims that another functioned called "Bit 15" was there to switch off emissions cleaning after about 16 miles (25 km) of driving. Apparently, the software helped reducing the application of AdBlue fluid, which helps eliminate harmful exhaust gases, resulting in some Mercedes diesels emitting NOx fumes up to 10 times higher than the legally permitted levels.
The German newspaper report cited e-mails from Mercedes' own engineers who questioned whether these software functions were legal. According to Autonews, a spokesman for Daimler declined to comment on the findings, stating that the automaker was fully cooperating with U.S. authorities.

7.8.4 Nissan

On May 2017 South Korea accused Nissan Motor Co Ltd of manipulating emissions on a diesel sport utility vehicle (Nissan Qashqai). It will fine Nissan Korea Co. 330 million won ($28,000) and recall 814 Qashqai vehicles sold since November. It also plans to file a complaint with prosecutors against Takehiko Kikuchi, the head of Nissan's South Korean operation.
The SUV's emission reduction device stopped operating when the engine's temperature reached 35 degrees Celsius, about 30 minutes after the engine begins to work.

"Usually, some cars turn off the emission reduction device when the temperature reaches 50 degrees Celsius, to prevent the engine from overheating. The Qashqai was the only vehicle that turned it off at 35 degrees, all auto experts expressed the opinion that it was clearly a manipulation of the emissions reduction device" told the officials. When the emission reduction device stopped working, the Nissan vehicle's level of emissions was about the same or slightly higher than that of Volkswagen diesel cars that were fined for cheating emissions.

Figure 106: Hong Dong-kon, a director at the South Korean Environment Ministry, speaks about Nissan Korea Co. Qashqai vehicles at the government complex in Sejong, South Korea

Nissan Motor Co. in Japan denied any wrongdoing. It said South Korean authorities' findings differed from those of the European Union, which concluded that Nissan vehicles used no illegal devices. The company said it will assess the situation and continue to work with South Korean authorities.

"Nissan has not and does not employ illegal defeat or cheat devices in any of the cars that we make," it said in a statement.

The South Korean government investigated 20 diesel car models sold in South Korea following the scandal over Volkswagen's admission that it had equipped cars with software that could limit emissions when cars were tested by regulators.

7.8.5 Mitsubishi

In April 2016, Mitsubishi Motors admitted to manipulating fuel consumption data of its cars. The scandal led to the end of Mitsubishi's independence. Later on it was announced that Mitsubishi Motors will – for all intents and purposes – be taken over by Nissan. To misstate fuel consumption is the same as misstating CO2 emissions. Despite being limited to the Japanese kei car oddity, the scandal was widely covered in the world media. Even if it didn't regard Diesel cars on the specific, to most people both consumption scandal and dieselgate makes no big differences, and the common thought about it was quite similar.

7.8.6 GM and Opel

On May 2017 GM admitted to overstating the fuel consumption of some of its crossovers. To misstate fuel consumption is the same as misstating CO2 emissions. The matter, along with GM's explanation that it was an "inadvertent error," was widely reported in the media.

On May 2016 some allegations rose up about GM's European Opel arm accused of using defeat devices in two of its diesel cars. Opel has been summoned to appear in front of an investigative committee of Germany's Transport Ministry. Netherland's RDW, the regulator that issued the EU type approval of Opel's Zafira Diesel, is considering a recall, and possibly a loss of the type approval, Germany's ARD News says. This is front-page news in Europe, it made headlines as far away as The Himalayan Times, but as far as the reporting in America goes, it didn't happen. The writing may be on the wall, but not in America. The incident has the potential to bring down GM's Opel in Europe just like Mitsubishi was brought in Japan.

Figure 107: Opel Zafira

8. INSTITUTIONAL ACTIONS

The Dieselgate could affect the awareness of some part of the market, but it led anyway to misleading thoughts and misperception about the topic, since most people just stopped at the layer of the problem and didn't detach the issue from the mere differences between real and test cycles.

The most tangible effect of those scandals are perceivable at the institutional level, where the major concerns about environment and pollution sum up and led to some drastic decisions that eventually affected everyday life of costumers. As stated in Chapter 3, emissions of cars are just a small part of the total amount of pollutant gases in the atmosphere, nevertheless cars are one of the most simple parameter to be controlled in big cities in order to try to reduce pollution.

8.1 France

France had already set a **target date of 2040 for an end to cars dependent on fossil fuels** and that this required speedier phase-outs in large cities. After that date, automakers will only be allowed to sell cars that run on electricity or other cleaner power. Hybrid cars will also be permitted.
Paris authorities plan to *banish all petrol and diesel-fueled cars by 2030*, Paris City Hall said on Thursday.

Figure 108: Paris pollution

The move marks an acceleration in plans to wean the country off gas-guzzlers and switch to electric vehicles in a city often obliged to impose temporary bans due to surges in particle pollution in the air.

8.2 UK

Figure 109: London pollution

Britain will **ban sales of new gasoline and diesel cars starting in 2040** as part of a bid to clean up the country's air. The blueprint highlighted roughly £1.4 billion ($1.8 billion) in government investment designed to help ensure that every vehicle on the road in Britain produces zero emissions by 2050.
Oxford has proposed banning all non-electric

vehicles from its center from 2020. This would make central Oxford the world's first zero-emissions zone according to the officials.

8.3 Germany

Deutsch government has still to implement a legislation about the ban of internal combustion cars. The strong predominance of German manufacturers in this sector has a big influence on political decisions. Nevertheless production of combustion engines is one of the main drivers of German economy.

Those are the words of Merkel when asked about a possible stop of combustion engines vehicles:

Figure 110: Billboard in Stuttgart, the most polluted city in Germany, inviting drivers to give up their cars to public transport due to record pollution.

"I cannot name an exact year yet, but the approach is right because if we quickly invest in more charging infrastructure and technology for electric cars, a general changeover will be structurally possible"

In February 2018 the Federal Administrative Court in Leipzig said the cities of Stuttgart and Dusseldorf could legally ban older, more polluting diesel cars from zones worst affected by pollution.

Cars that meet Euro-4 emissions standards could be banned from Stuttgart from next January, while Euro-5 vehicles should not be banned until Sept. 1, 2019, four years after the introduction of the latest Euro-6 standard. Tradesmen and some residents should be exempted, the court added.

Environment Minister Barbara Hendricks said bans could still be avoided if automakers agree to pay to upgrade the exhaust cleaning systems of older diesels.

The ruling was praised by environmental groups but angered many politicians and business lobbies who said millions of drivers might end up unable to use or sell vehicles they bought in good faith. Merkel said the government would discuss with regions and municipalities how to proceed, while her ministers said they still hoped bans could be averted by steps to bolster public transport and get automakers to improve emissions systems.

If bans widespread, it could cause serious problems since there are approximately 15 million diesel-powered vehicles in Germany. Only around 2.7 million meet Euro-6 regulations which means there are roughly 12.3 million vehicles which could be banned from cities in the near future.

8.4 India

Figure 111: New Delhi, the most polluted city in the world

The government said earlier this year that every vehicle sold in the country should be powered by electricity by 2030.

"This is an aspirational target, ultimately the logic of markets will prevail."

In India, which suffers from an acute air quality problem, are located the world's most polluted cities. But it's also a country where policymakers can make a big difference.
The number of cars on the country's roads is expected to explode over the coming years as four-wheel vehicles become more affordable for the middle class. The risk of a very dangerous increase of pollutants in the big cities is extreme.

8.5 Norway

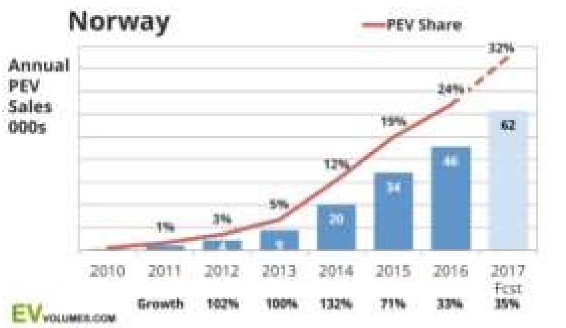


Figure 112: Trends of EV sales in Norway 2010-2017

The government's transportation plan is very strict. all new passenger cars and vans sold in 2025 should be zero-emission vehicles. Norway is leading the way. About 32% of all cars sold in the country last year were electric or hybrid vehicles, thanks to strong incentives from the government.
Tesla was in December 2017 the most popular automaker in the country. Norway now has more than 10 percent of the global all-electric car fleet.

8.6 China

Figure 113: Critical level of pollution in Beijing

China, the world's biggest vehicle market and producer, is considering a ban on the production and sale of fossil fuel cars in a major boost to the production of electric vehicles as Beijing seeks to ease pollution, that is still one of the biggest issue for the country.

Xin Guobin, vice-minister of industry and information technology, told that his ministry had started “relevant research” and was working on a timetable for China. The data is supposed to be 2040 as for UK and France.

The government introduced in June 2017 a draft regulation to compel vehicle manufacturers to produce more electrically powered vehicles by 2020 through a complex quota system.
As the measure looms, foreign vehicle manufacturers have announced plans to boost the production of electric cars in China. In 2017, 500.000 cars sold in China were electric or hybrids.

8.7 Others

At least eight other countries have electric car sales targets in place, according to the International Energy Agency: Austria, Denmark, Ireland, Japan, the Netherlands, Portugal, Korea and Spain have set official targets for electric car sales. The United States doesn't have a federal policy, but at least eight states have set out goals.

8.8 Italy

Italy is still one of those country that hasn’t announced any official plan for internal combustion engines even though it is home of some of the most polluted cities of all Europe, Turin, Milan, Bologna and Naples.
In the most critical situations, city’s government are applying some temporary bans of cars according to their Euro classification, concentrating their focus on Diesel until Euro 4 and Petrol until Euro 0.
In the most critical cases the limits were extended to the upper classes of homologation.

Figure 114 Pollution in Po Valley. the conformation of the territory doesn't help the air circulation.

The limits triggers after the consecutive achievement for four days of the daily limit value of Pm10 equal to 50 micrograms per cubic meter.

In February 2018, the major of **Rome**, Virginia Raggi, during a the C40 meeting in Mexico City, announced officially the ban of passengers diesel cars from Rome city centre starting from 2024. This is the first city in Italy to adopt serious countermeasure to pollution.

“Our cities risk facing an unexpected challenge. We are increasingly witnessing extreme problems, as is happening in Lazio, where in one day the rain of a whole month is poured out on the ground; or even unusual snowfall at low altitude as in those days is investing Italy. For this we must act

quickly. Along with other major world capitals, Rome has decided to engage in the front line. If we want to intervene seriously, we need to have courage to face strong measures. We must act on the causes and not only on the effects "

Also the second most important city, **Milan**, just announced new countermeasures. In 2030 Milan aims to free itself from the traffic of the most polluting vehicles, up to diesel Euro 6 included. It will start from October 2020 with the prohibition of circulation up to Euro 3 diesel throughout the city, in 2024 the ban will include vehicles up to Euro 5. The fleet of buses will be fully electric by 2030.

9. MARKET ANALYSIS

9.1 Market Scenario

Before going deep in analysing the effect of the Dieselgate and the new emissions' standards on the sales of new cars, is useful to have a broad view of the car market up to date.
In 2017 three different groups reached the milestone of 10 million cars sold worldwide, in the order the Alliance **Renault-Nissan**, VW Group and Toyota Group.
The former jumped in 1st position in the last year thanks to the acquisition of Mitsubishi: in detail, sales of Nissan Motor reached 5.82 million in 2017, while Renault recorded sales of 3.76 million. Mitsubishi's total sales reached 1.03 million in 2017, keeping the total of the Franco-Japanese Group for 2017 at around 10.61 million vehicles. The "secret" of the performance achieved by the Renault-Nissan Alliance was probably to try to increase sales volumes, achieving heavy economies of scale between the various associated brands and consequence, including self-driving cars, electric and new mobility services.
VW Group, which had been the best seller in 2016, sold 10,5 million units while **Toyota Motor** won the second place in 2016, sold 10.2 million units last year.
Following the acquisition of Opel/Vauxhall form PSA, **General Motors** fell to 5th place, overcome by **Huyndai-Kia**, that, for the first time after years of continuous grow, saw their sales decreasing.
Follow in order, **Ford** and **Honda,** while **Fiat Chrysler Automobiles** set at 8th place with a total of 4,8 million cars sold. Thanks to the surplus given by Opel, **PSA Group** gain one spot to 9th place against **Suzuki** that fell at 10th.

		SALES [millions]	Var. %
1	Renault-Nissan Alliance	10,6	6,3
2	Volkswagen Group	10,5	3,9
3	Toyota M.C	10,2	1,7
4	Hyundai-Kia	7,2	-8,3
5	General Motors	6,8	0,5
6	Ford M.C	6,2	-1,4
7	Honda M.C	5,3	8,3
8	F.C.A	4,8	1,8
9	P.S.A	4,1	30.1
10	Suzuki	3,1	11,1

Table 23: Manufacturers ranking 2017

Source: GAD (Global Auto Database)

As far as 2016, China, Europe, and the United States are the largest passenger car markets worldwide. **Diesel cars are mostly sold in Europe (65% of all diesel car sales worldwide)**, India (12%), and South Korea (6%). Hybrid cars are particularly popular in Japan (60% of all hybrid car sales worldwide, due to the almost monopoly of Japanese automakers and their wide offer of hybrids). For electric cars, more than 40% of the global production is currently sold in China.

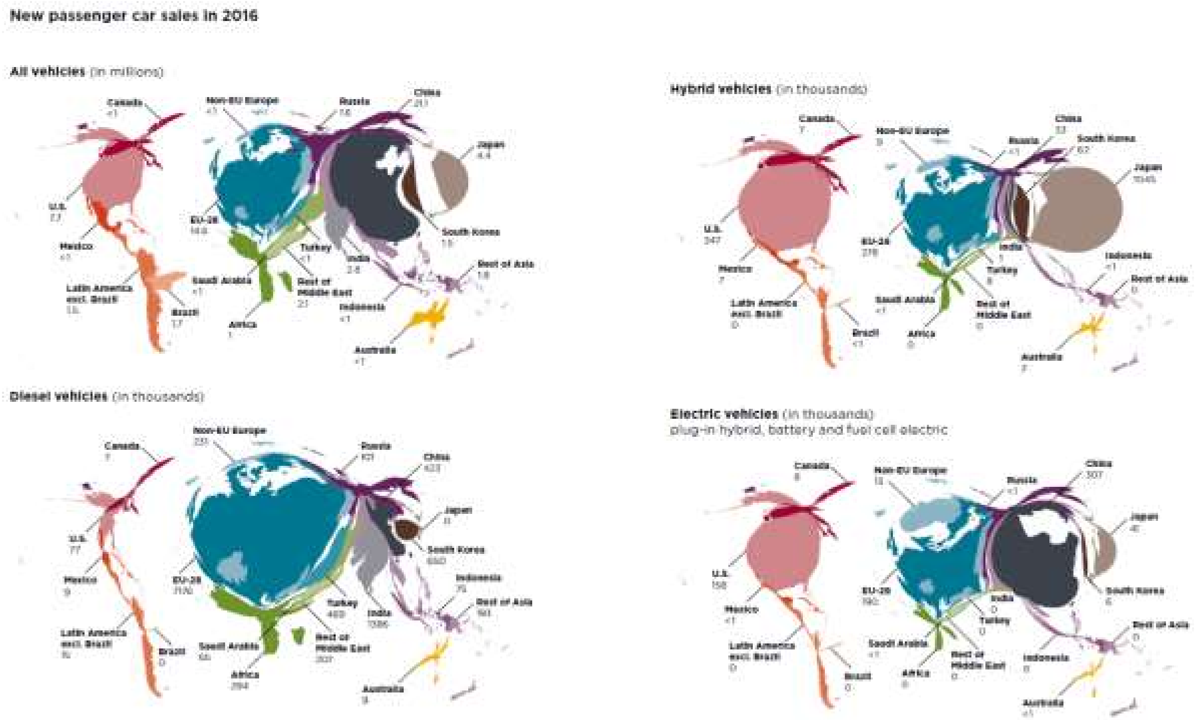


Figure 115: New Passenger car sales in 2016

Source: International Council on Clean Transportation Europe

New car registrations in the **EU** increased to more than 14 million in 2016. That number is nearly the same as in the years 2001–2007, before the economic crisis that hit new car sales in Southern European countries particularly hard. Registrations in the EU are dominated by the larger Member States; the three largest alone (Germany, France, United Kingdom) account for nearly 60% of the total. Germany is the largest market, with a 23 % share of the overall European market. Registrations in Germany dropped in 2006–2008, then rose in 2009 and from that point on increased again to around 3.4 million vehicles per year. Since 2014 sales in Spain and Italy are again trending upward sharply.

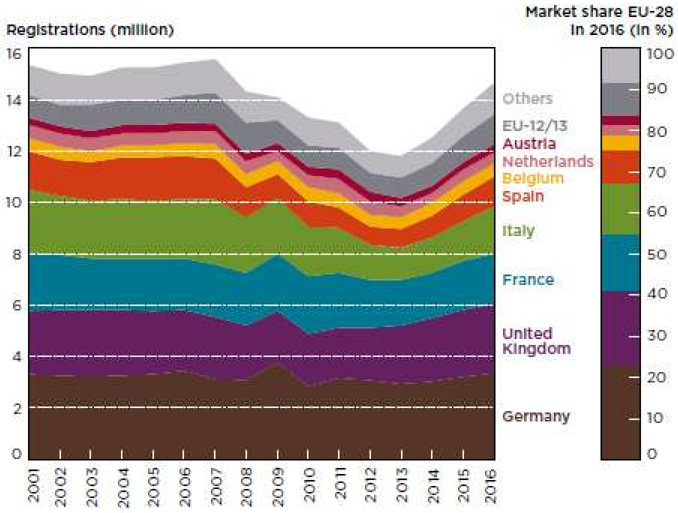


Figure 116: 2016 registrations in Europe by country

As in previous years, by far the strongest growth in vehicle sales took place in the sport utility vehicle (SUV) segment (I0,I1,I2). This constant growth is at the expense of MPV and Sedan segment, whose market share are falling constantly.

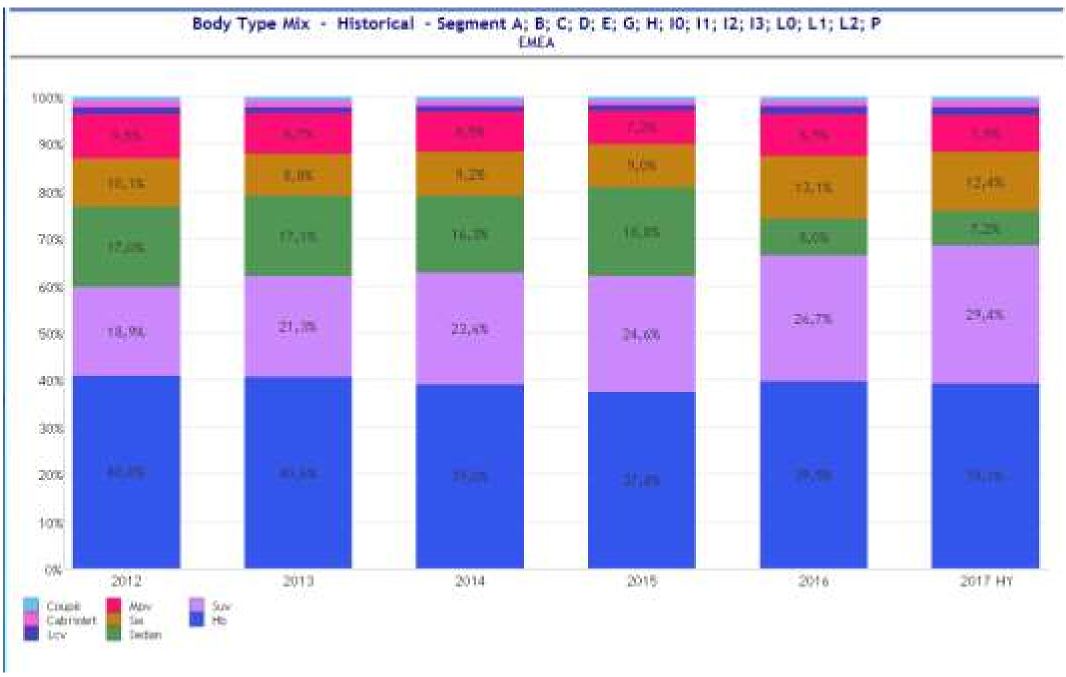


Figure 117: Body Type mix trend per year

Looking at the volumes of every segment in detail it is inferable how the EU market is mainly pulled by the B and C segment, with the latter that has always played the major role until 2017, when the former has performed the overcome by more than 100.000 units. Together they account for more than 40% of new cars registrations.

Segment	2013	2014	2015	2016	2017
Total	12.221,135	12.888,714	14.071,950	14.956,835	15.365,899
A	1.168,183	1.175,180	1.280,012	1.279,028	1.306,289
B	2.840,644	2.861,043	3.040,065	3.150,452	3.212,899
C	2.735,110	2.917,178	3.089,233	3.184,756	3.110,718
D	1.160,954	1.150,160	1.286,855	1.338,552	1.243,099
E	396,761	389,999	387,422	370,349	398,792
G	46,055	55,311	52,993	54,173	59,667
H	97,011	83,963	95,193	110,483	111,172
I0	521,063	784,735	1.108,352	1.286,570	1.344,467
I1	990,113	1.125,802	1.259,439	1.594,860	2.010,076
I2	455,675	507,298	616,737	713,382	858,274
I3	189,148	210,856	266,407	307,528	290,574
L0	409,872	424,602	369,645	317,718	280,911
L1	889,388	868,429	874,676	840,161	729,234
L2	133,951	144,182	141,359	186,518	172,519
P	187,207	189,976	203,562	222,305	237,208

Table 24: EU car registrations per segment 2013-2017

9.2 Diesel Trends Europe.

In order to visually understand the effect of the Dieselgate on the markets, an analysis of the trend of Diesel fuelled cars sold in EU by segment has been performed through elaboration of Jato data. Every segment has specific peculiarities and a different mix of diesel that was affected by last years' events more or less according to markets.

9.2.1 A Segment

Segment A has always been dominated by Petrol, with a small quote of Diesel trained by the 2 best seller, **Fiat Panda** and **500**, that reached the peak of 11,7% of market share in 2008. Nowadays most competitors don't offer anymore any Diesel alternative on their engine-line.
Small cars are used mainly in the big cities, where limitations of Diesel have become pretty common in the last years, thus enhancing a further decrease of this engine choice between concerned customers. The biggest reason-to-buy of this segment is the price, and Diesel are no more competitive due to the big price increase requested by the Euro 6 regulations. By the end of 2018, with the introduction of Euro6D engines, is likely that also Fiat will give up on Diesel for both Panda and 500.
The ones looking for fuel economy are moving towards alternative fuels as LPG and CNG.
Small electric cars are also starting to diffusing in the big cities. Smart is already offering a full-electric alternative for its vehicles, and in the near future they will completely substitute internal combustion engines.

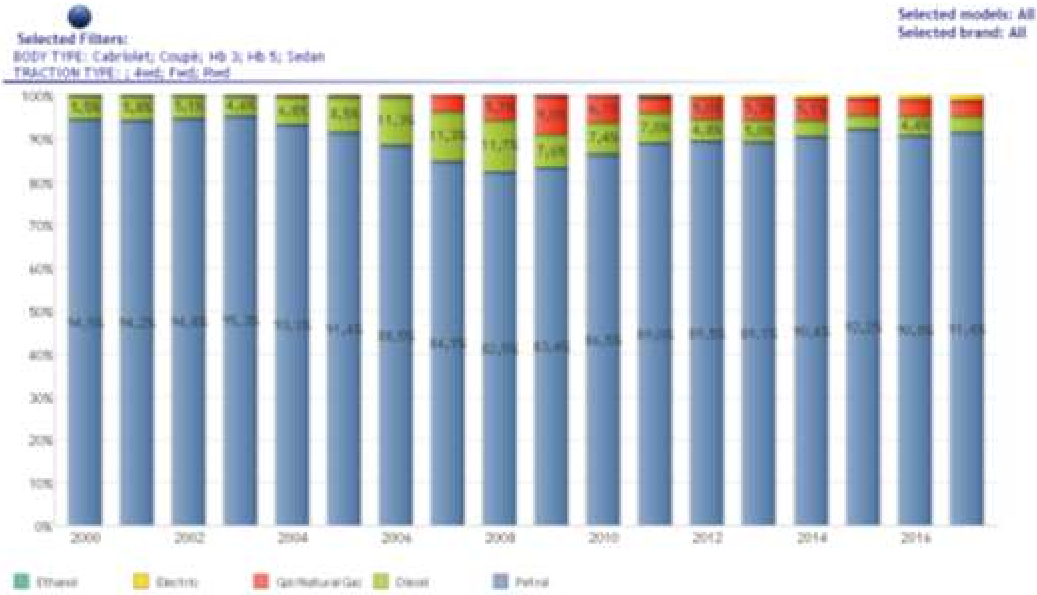


Figure 118: Segment A Fuel Mix trend 2000-2017

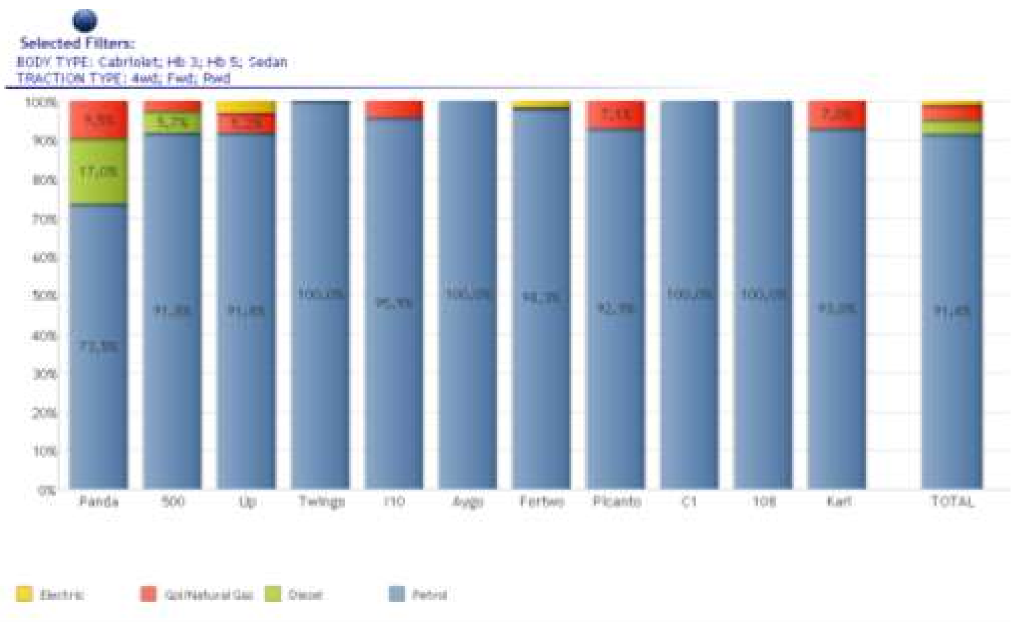


Figure 119: Segment A Fuel Mix H1 2017

9.2.2 B Segment

Concerning segment B, the quote of Diesel is much higher than segment A. The trend has been positive until year 2011, when it has consequently started to decrease losing 16pp up to 2017. Almost all manufacturers are still offering Diesel alternative even if some have already announced a stop of investments for future version of theirs cars, like Renault with the Clio.

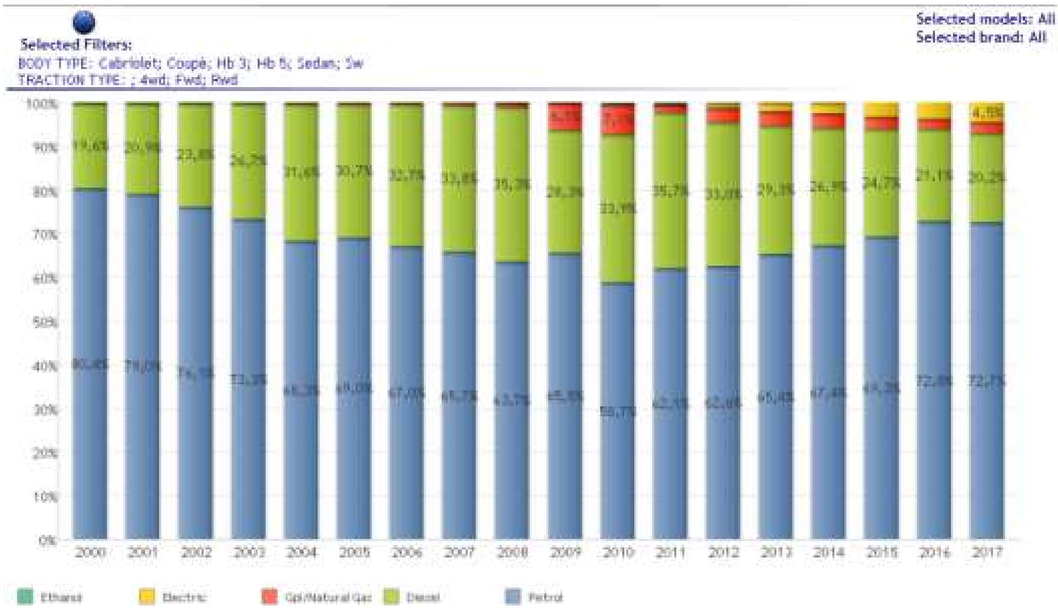


Figure 120. Segment B Fuel Mix trend 2000-2017

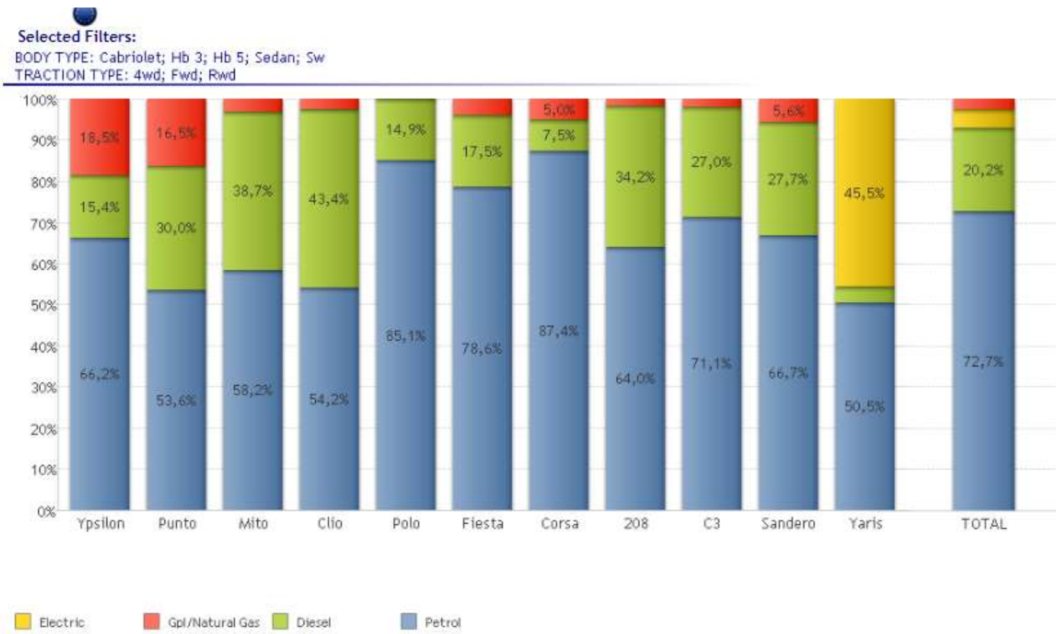


Figure 121: Segment B Fuel Mix 2017

9.2.2.1 Toyota Yaris Case

Figure 122: Toyota Yaris Hybrid '17

In 2017 Toyota Motor Co. announced that it won't be offering anymore the Diesel engine in Italy, Yaris included.
From a deeper analysis of the Yaris case the reasons of this choice are easily inferable. The presence of the Hybrid alternative has been a major driver in the decrease of Diesel among customers. Since its launch, hybrid has been promoted widely by Toyota as the most cost efficient alternative, promising a mileage of more than 30 Km/l in city driving, taking the usual value proposition of Diesels.
Strong of more than 20 years of experience, Toyota was able to offer this motorization with a price surplus of only 2000€ compared to Diesel, plus all the incentives of every specific country for green car.
The effect on the market was almost immediate, as shown in Figure 123 and 124.

In Europe, after 1 year of commercialization, Hybrids had already doubled the share of Diesel and by 2017 the latter sank to less than 5% while the former rose up to 46% with a positive trend that is only going to further increase.
In Italy the effects were quite similar, but in this case Hybrid has already overcome Petrol since 2016. In this case the incentives, as the exemption of the annual taxes, free parking, and free ZTL pass, played in favour of the Hybrid.

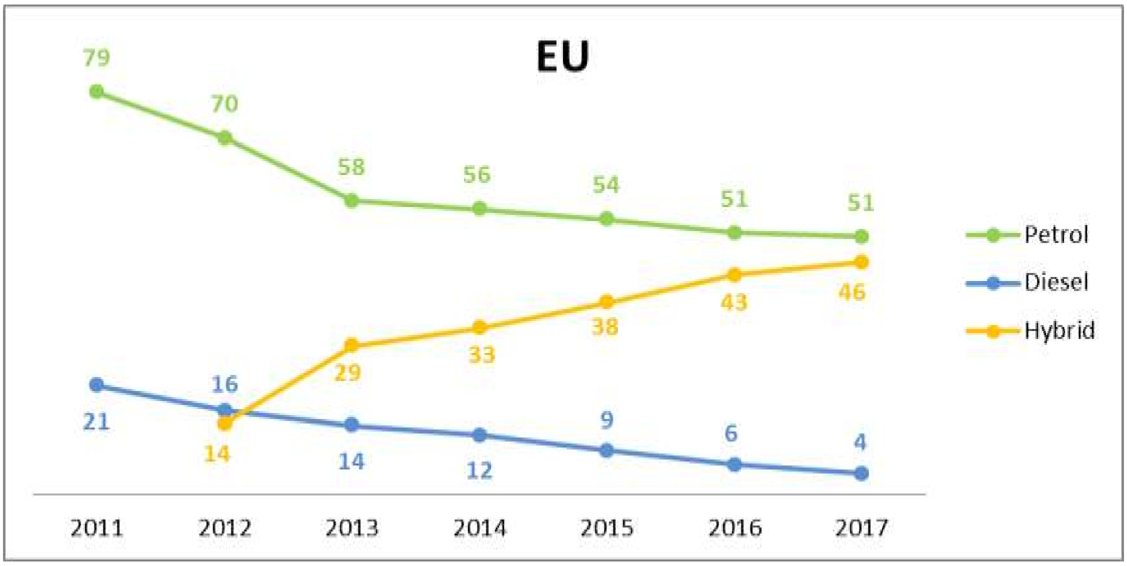


Figure 123: Toyota Yaris Fuel trends in Europe

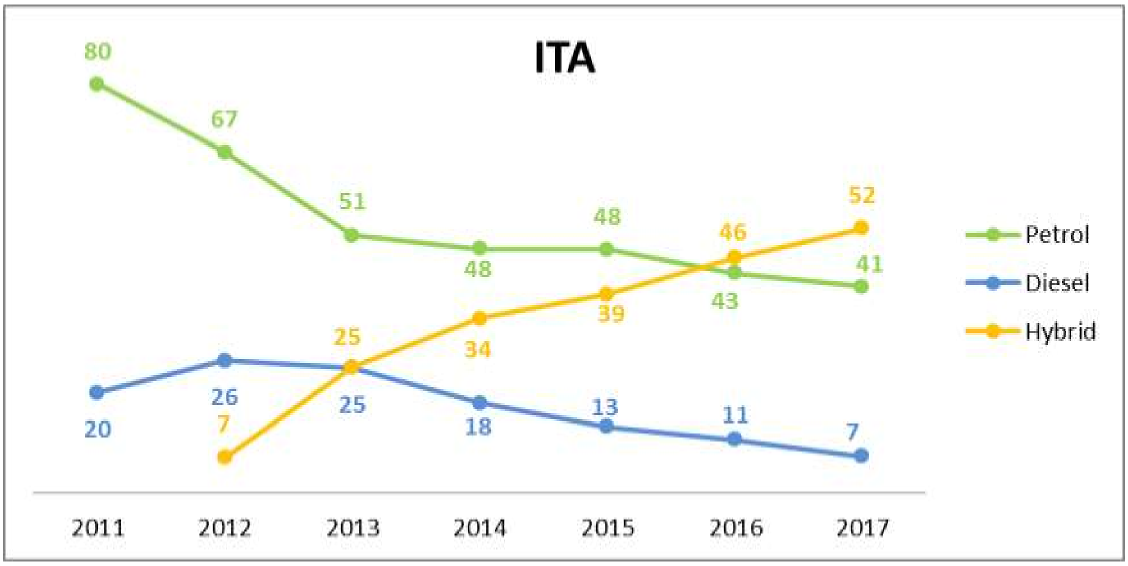


Figure 124: Toyota Yaris Fuel trends in Italy

9.2.3 C Segment

C-Segment is the biggest segment in Europe for Diesel engines, selling almost 1,5 million diesel cars in 2017 and a record 1,69 million in 2015. Its market share reached almost 60% in 2012 but is being affected by the trend of the last years too. After overcoming Petrol in 2003, in 2018 Diesel is going to yield the crown to the former and it will suffer by the sudden arrival of new hybrids versions, together with CNG and LPG which are proposed by main players.

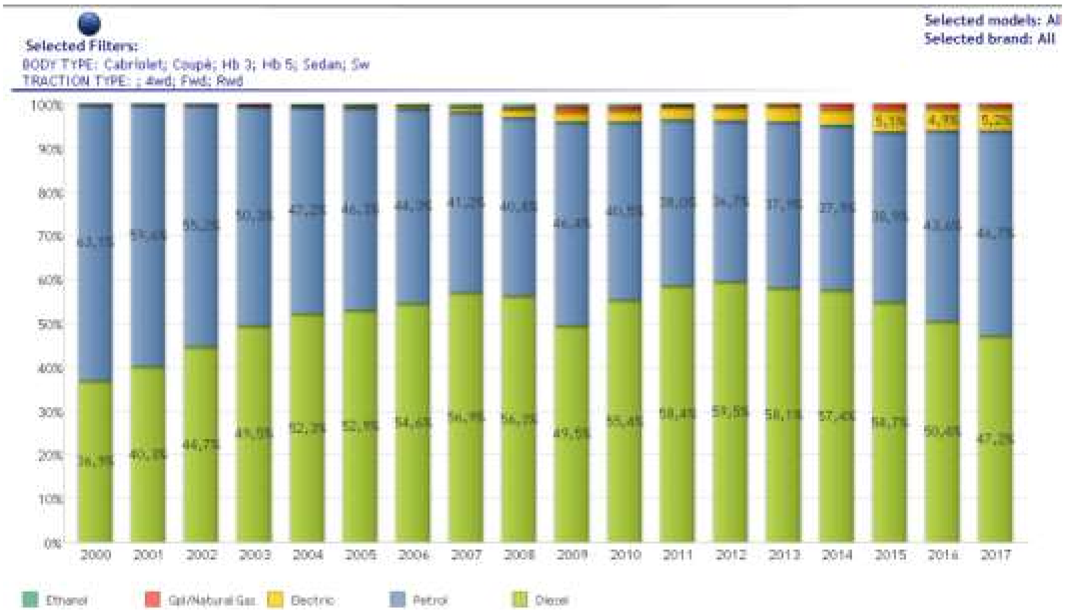


Figure 125: Segment C Fuel Mix Trend 2000-2017

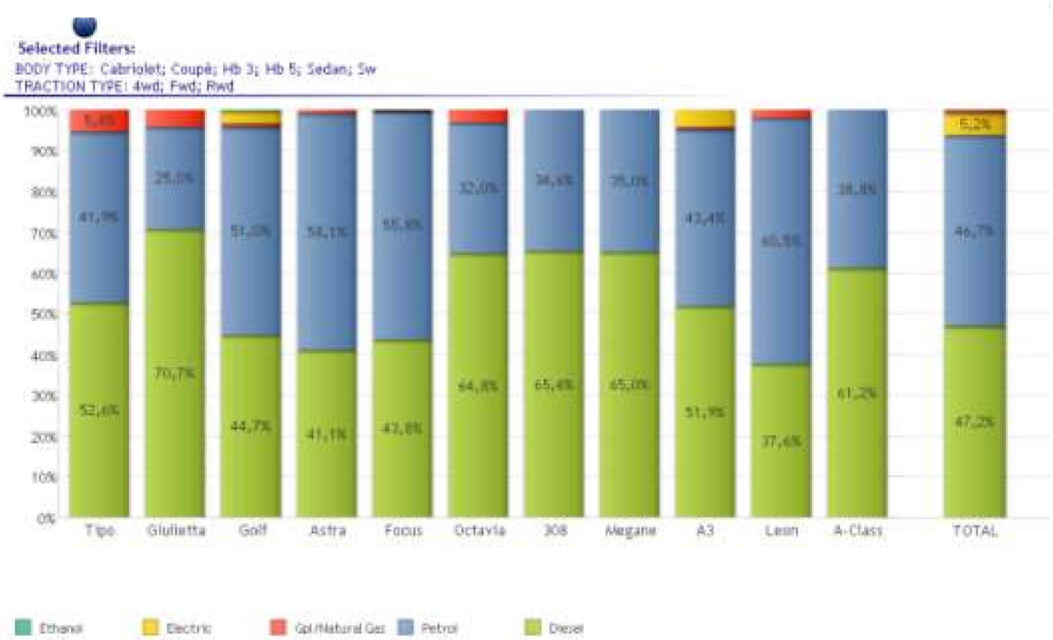


Figure 126: Segment C Fuel Mix 2017

9.2.3.1 Toyota Auris Case

Figure 127: Toyota Auris Hybrid '17

As for the Yaris, also for the C-segment model of Toyota, the Auris, went through the same process of the Yaris. In this case the results are even more symbolic.
Hybrids took only 4 years to completely overcome both Petrol and Diesel, with the latter that in the last 2 years decreased loosing on average 5pp every year. Is no surprise that Toyota eventually withdrew it from some market. By 2017, the amount of Auris hybrids sold in Europe in twice the sum of the other motorizations.
Hybrids were pushed by the fleets, in particulars taxies in the major cities in Europe, that replaced their old diesels with the new hybrids, following the good reputation of the Hero Model of Toyota, the Prius.

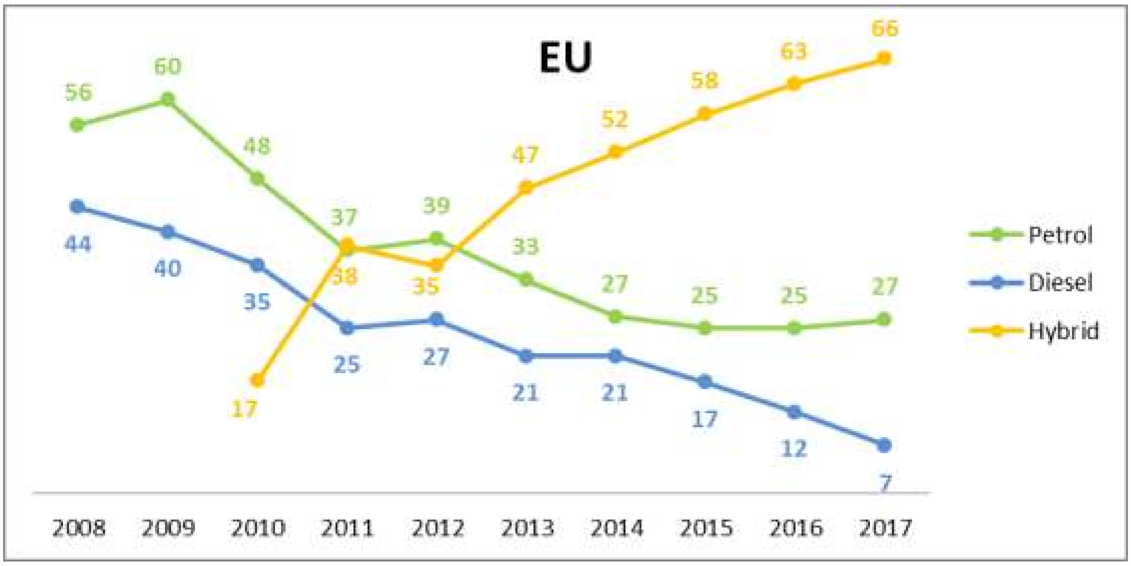


Figure 128. Toyota Auris Fuel trends in Europe

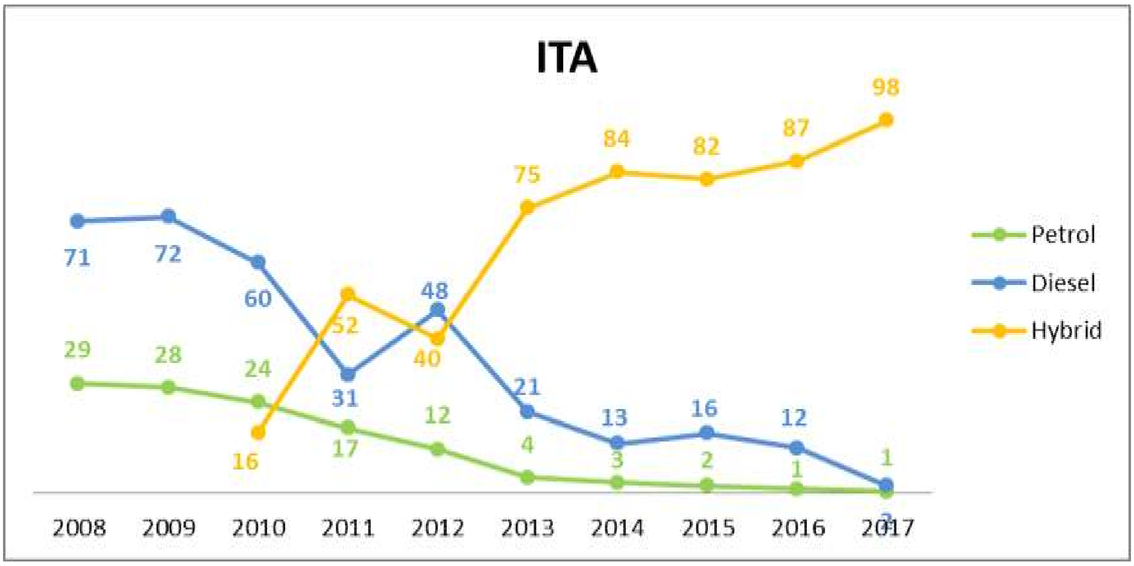


Figure 129. Toyota Auris Fuel trends in Italy

9.2.4 D Segment

In the higher segment, D, the predominance of diesel towards other motorization is overwhelming. The trend has been increasing until 2014, when it reached the 82,75% market share. This kind of cars are usually driven for high distances at motorway speeds, thus enhancing the advantages of diesel, as the fuel economy at constant speed.

After the Dieselgate, anyway, also this kind of cars underwent a not negligible loss in diesel shares, with the Petrol gaining back part of the market, pushed by a new generation of engines, capable of much better fuel economy.

In the near future big investments in hybridization are going to take over the market, as all the major manufacturers have announced plans to introduce one or more version aided by electricity. Some of them have already tried to match the electric motor with a Diesel, but with results not very successful (Peugeot 508 RXH, Volvo V60 Diesel Hybrid).

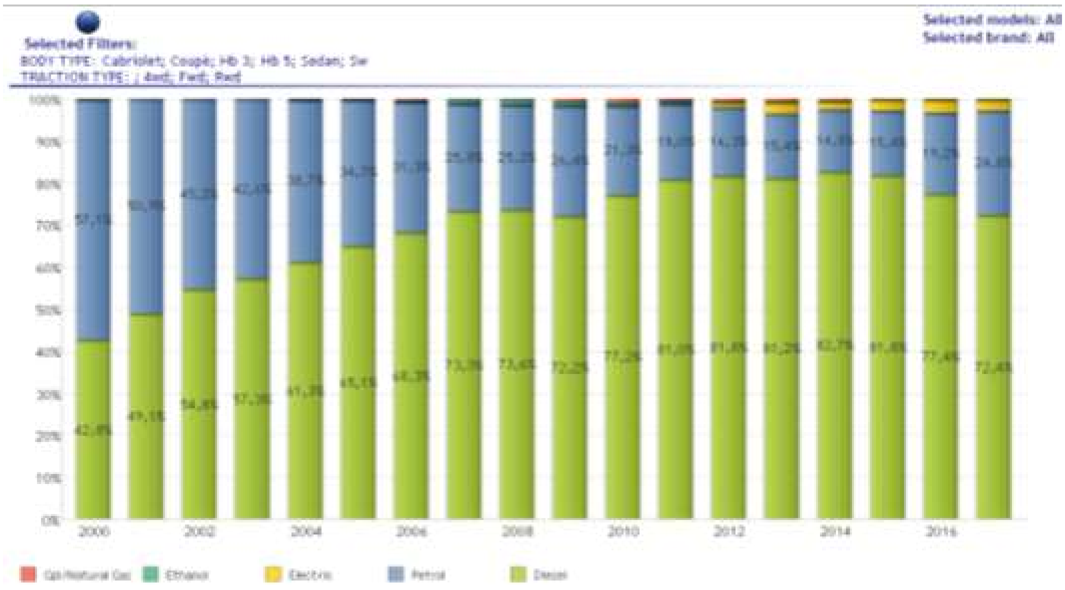


Figure 130: Segment D Fuel Mix trend 2000-2017

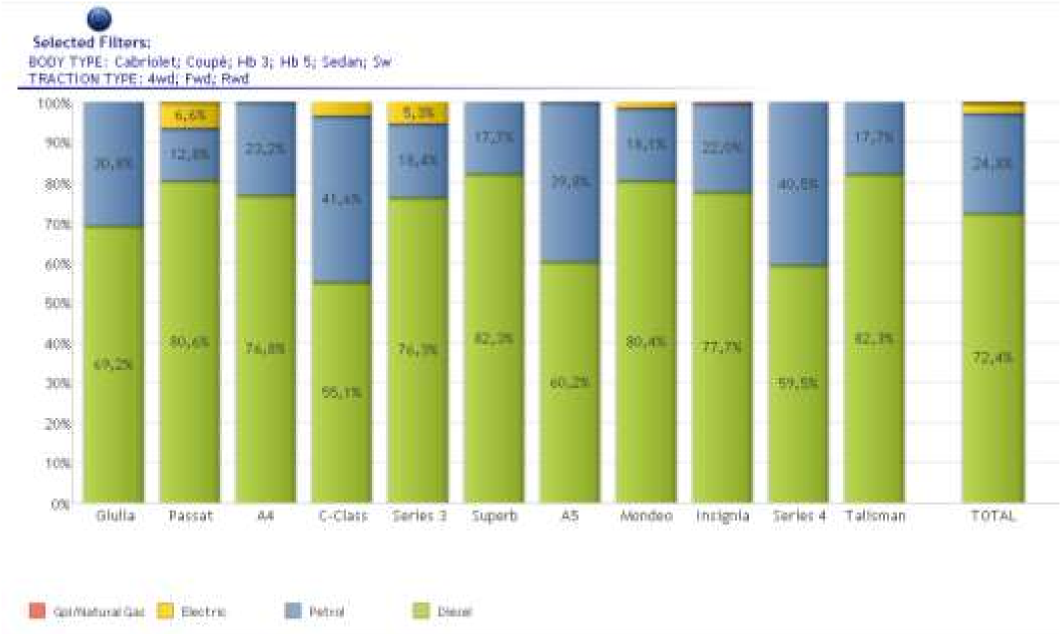


Figure 131: Segment D Fuel Mix H1 2017

9.2.5 E Segment



As for D segment, also the E one followed the same market processes in the last year.

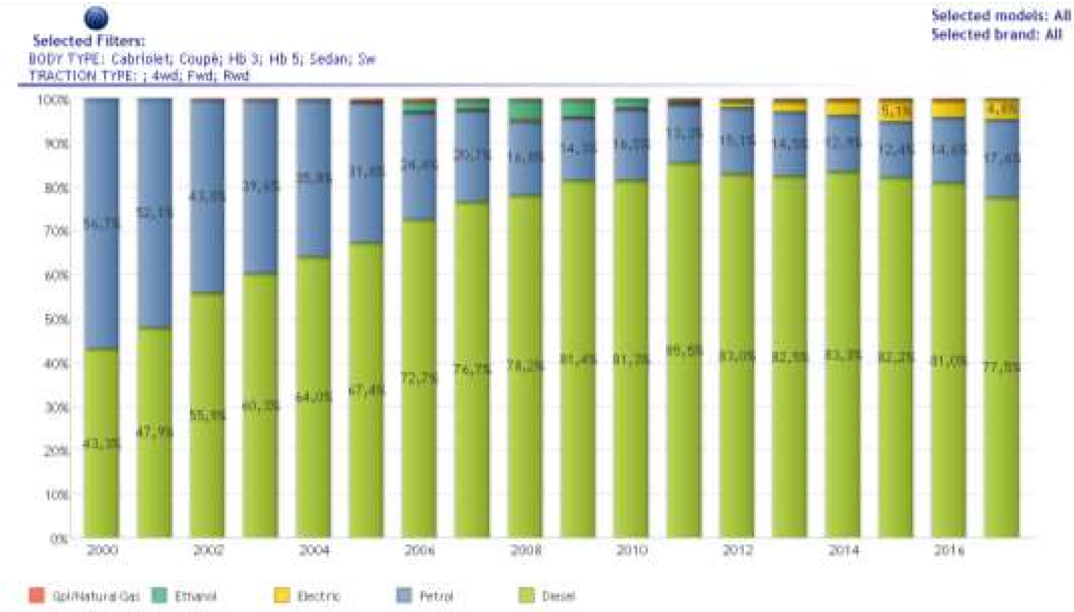


Figure 132: Segment E Fuel Mix trend 2000-2017

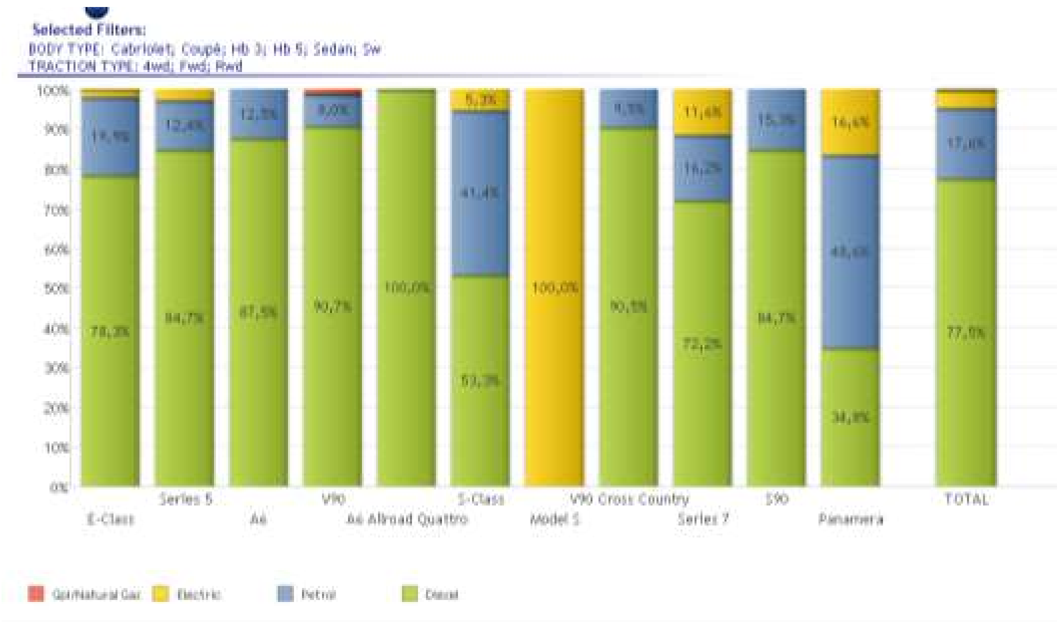


Figure 133: Segment E Fuel Mix H1 2017

9.2.6 I0 Segment

The I0 segment is one the fastest growing segment in EU and during the growth period sales were pushed by diesels. In the last year market share of diesel is decreasing, overcome by Petrol in 2016. Also in this segment Toyota has chosen a no diesel approach for its car, the C-HR, that in some markets, like Italy, is neither available with Petrol.

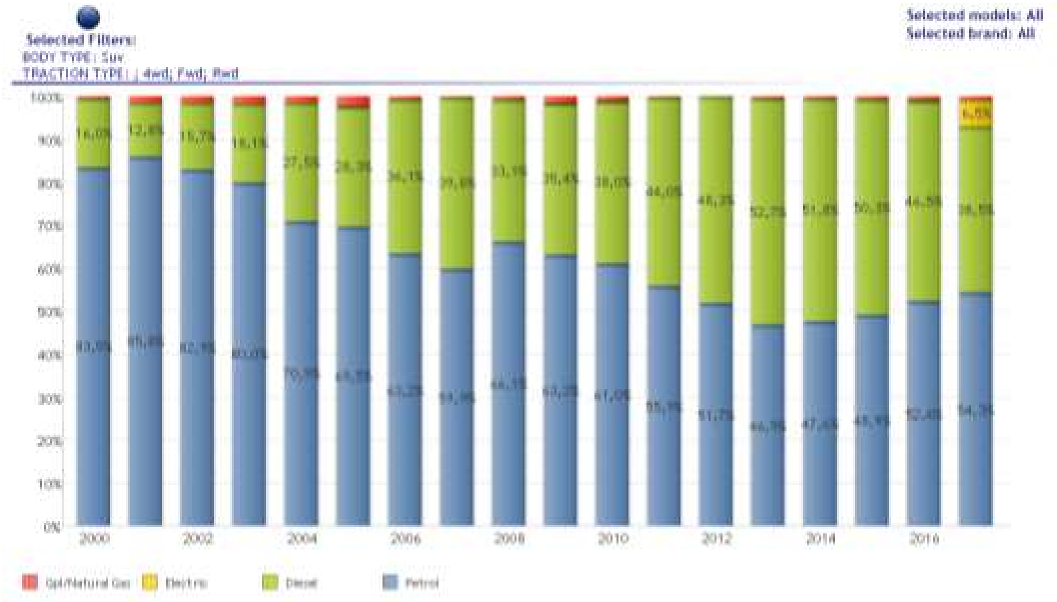


Figure 135: Segment I0 Fuel Mix trend 2000-2017

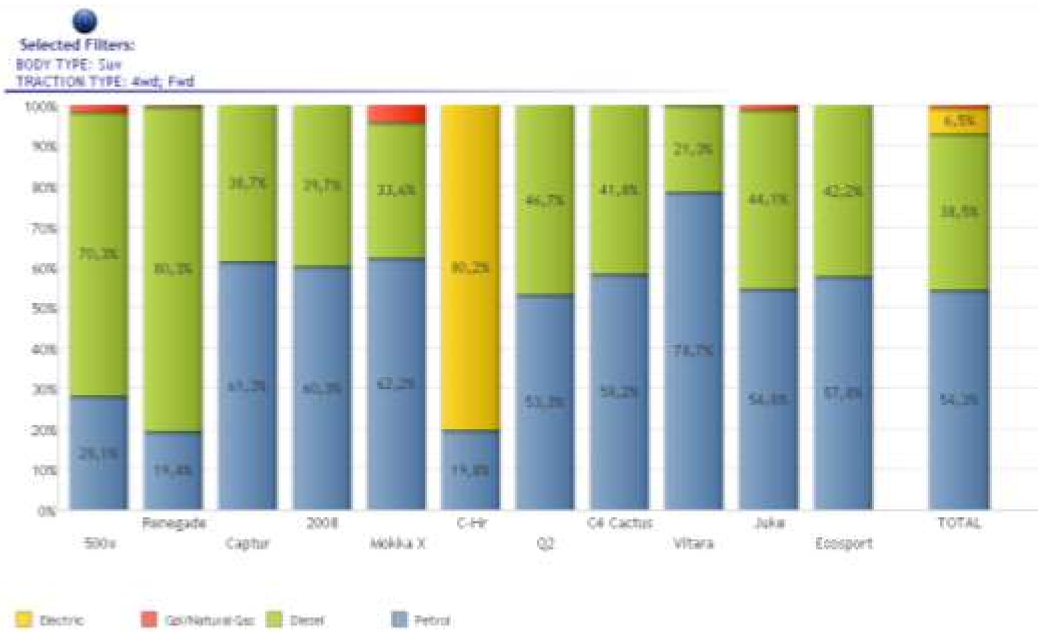


Figure 134: Segment I0 Fuel Mix H1 2017

9.2.7 I1 Segment



The I0 segment, the SUV corresponding of C, is the fastest growing segment in EU. As the latter, its weight in the sales of diesel in Europe is very high: all the most sold models have their modal engine among the diesel ones. However in the last 2 years diesels lost 12pp in market share, keeping a quote almost double than petrol.

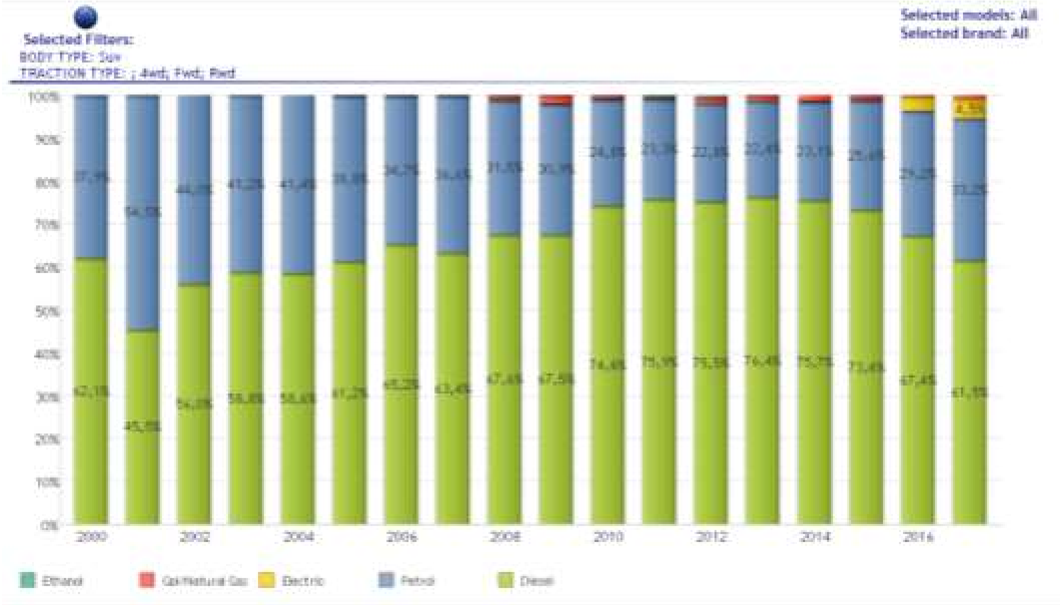


Figure 136: Segment I1 Fuel Mix trend 2000-2017

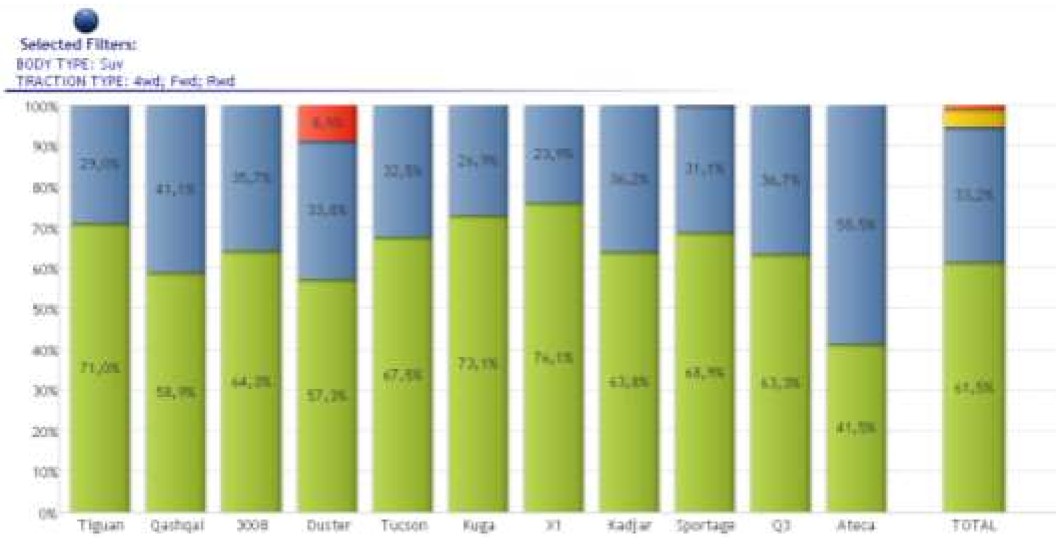


Figure 137: Segment I1 Fuel Mix H1 2017

9.2.8 I2 Segment

Large SUVs are still preferred equipped with diesel motorizations, that better fit this kind of vehicles, thanks to higher torque and good fuel economy. Petrol are usually reserved to high performance versions. Different case for Lexus, where the hybrid version represents almost 100% of sales.

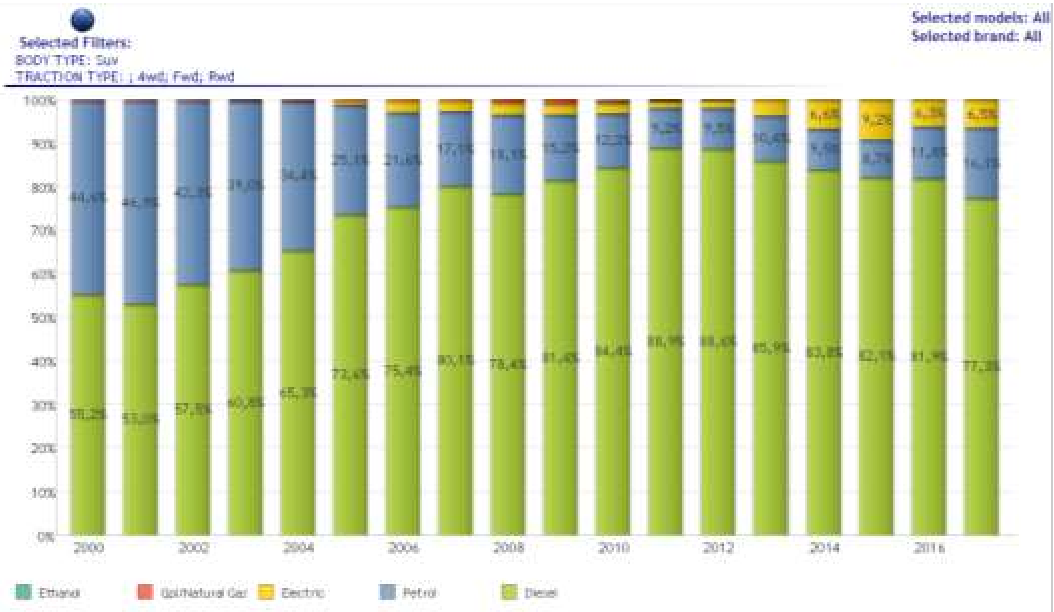


Figure 138. Segment I2 Fuel Mix trend 2000-2017

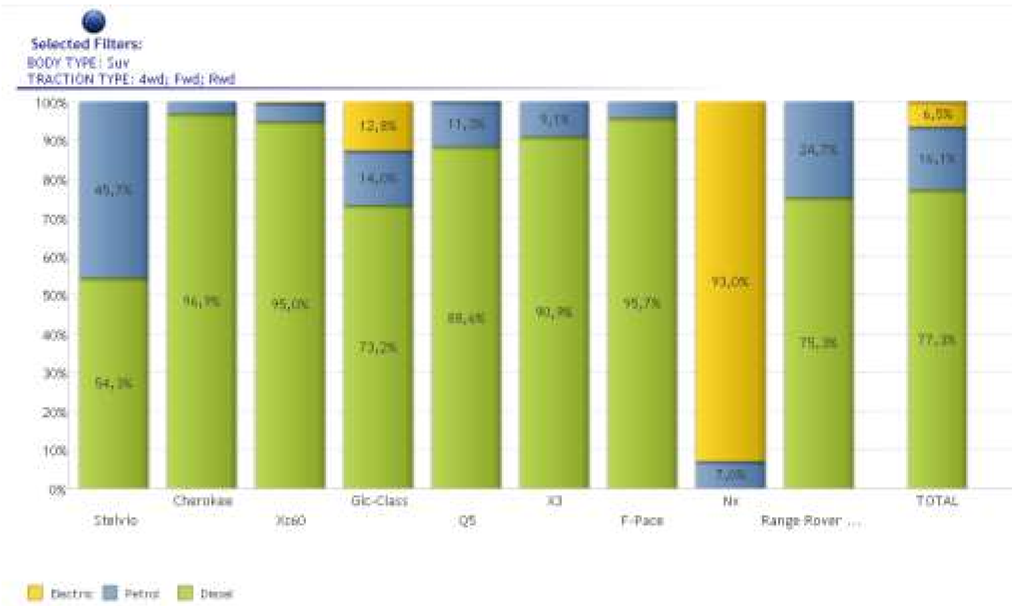


Figure 139: Segment I2 Fuel Mix H1 2017

9.2.9 I3 Segment

As far as big SUVs are concerned, diesels have always been the major choice, right until 2014 when a record market share of 94,3% was registered. The combined effect of Dieselgate and the increasing number of hybrids alternative has then led to the beginning of a fast decrease of the quote.

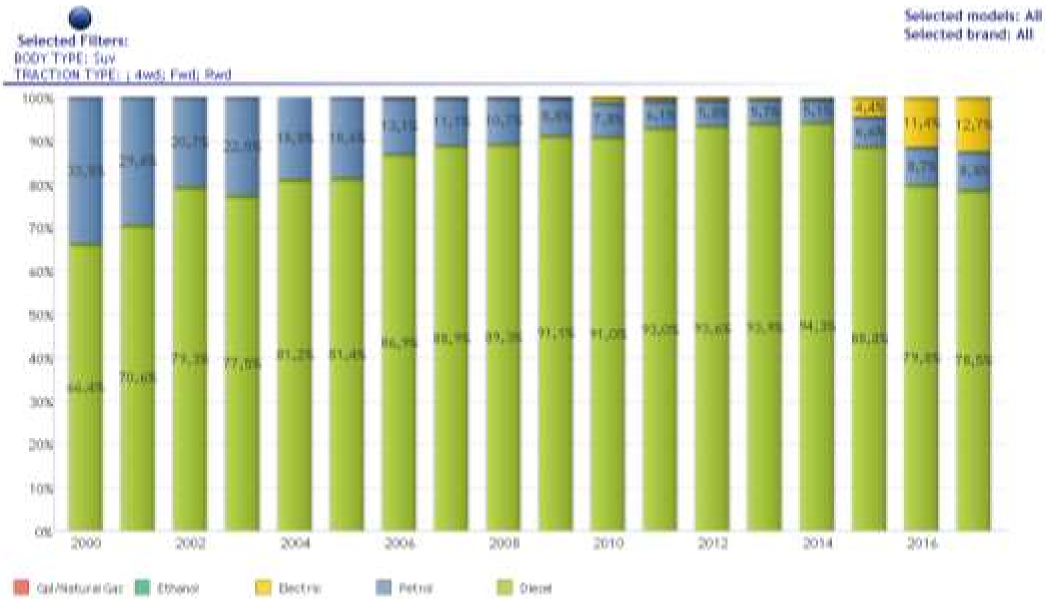


Figure 140: Segment I3 Fuel Mix trend 2000-2017

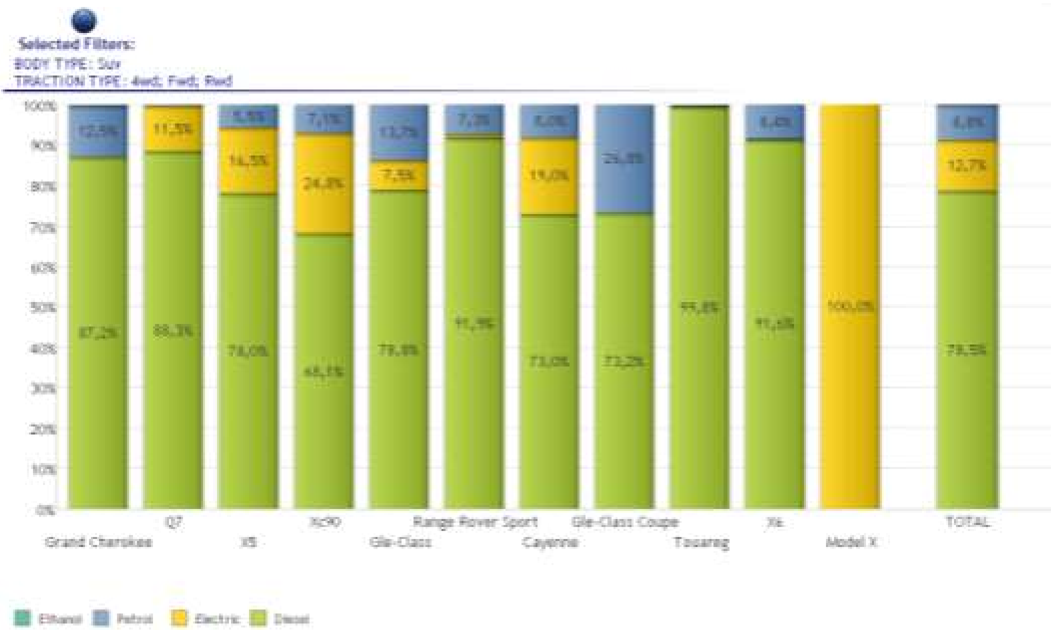


Figure 141: Segment I3 Fuel Mix H1 2017 Segment

9.2.10 L0 Segment

Small MPVs segment has not suffered the Dieselgate as much as the previous ones, with a quote loss of less than 5 pp in the last 2 years. That is due mainly to the effect of its best-seller, the Fiat 500L, which does still sell 68% of its versions equipped with Multijets. Competitors instead show a different fuel mix, with a prevalence of petrol.

The segment overall has lost a big amount of sales, cannibalized by SUVs.

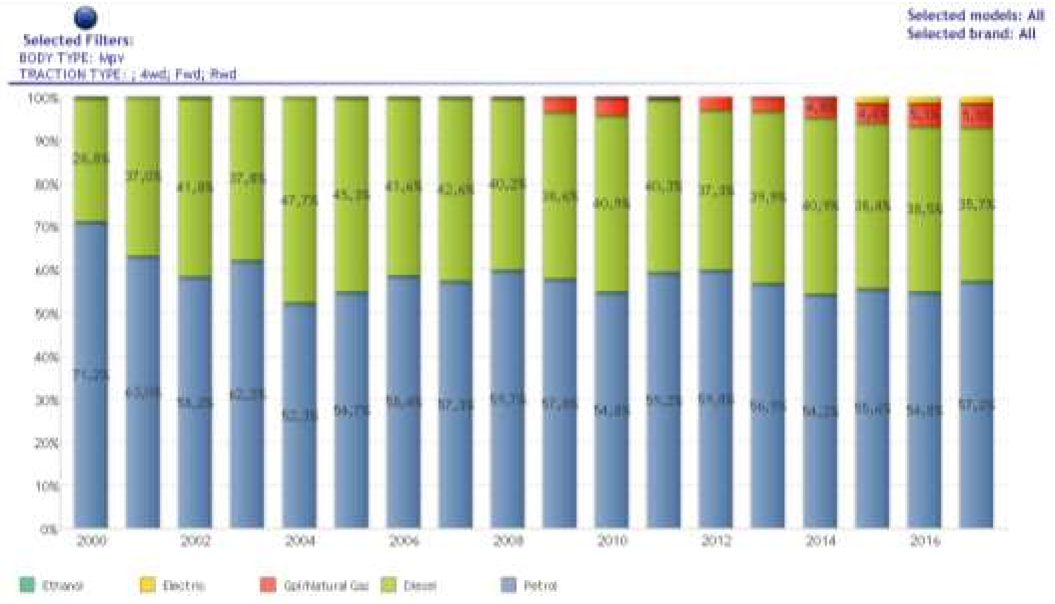


Figure 142: Segment L0 Fuel Mix trend 2000-2017

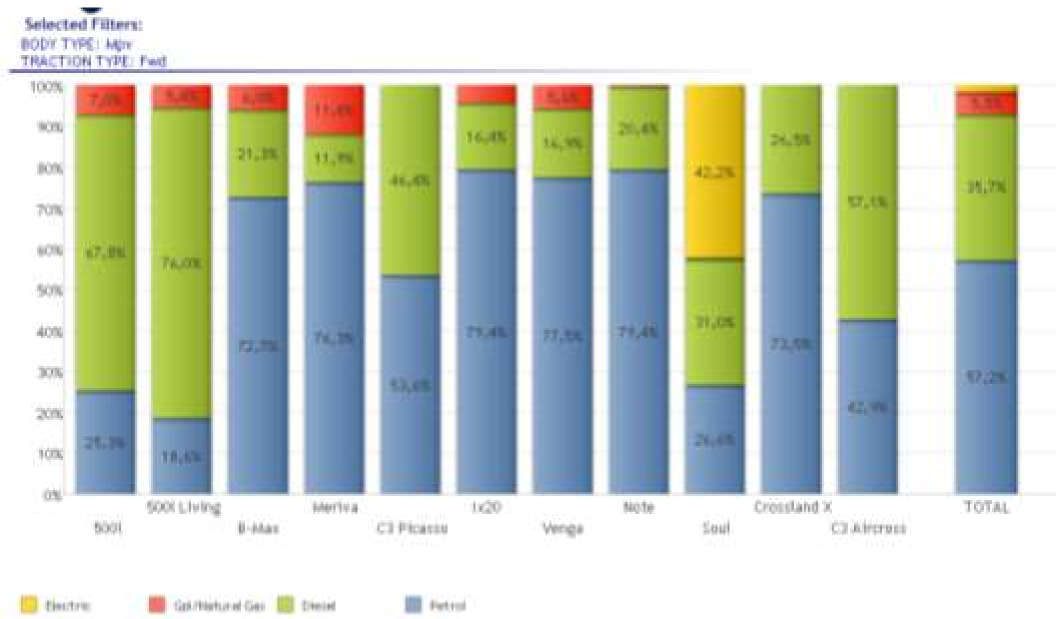


Figure 143: Segment L0 Fuel Mix Fuel Mix H1 2017 Segment

9.2.11 L1 Segment

Medium MPVs show instead a bigger loose in diesel rate in the last years. Diesel engines have lost 16 pp in 4 years while hybrids are slowly gaining some quotes.

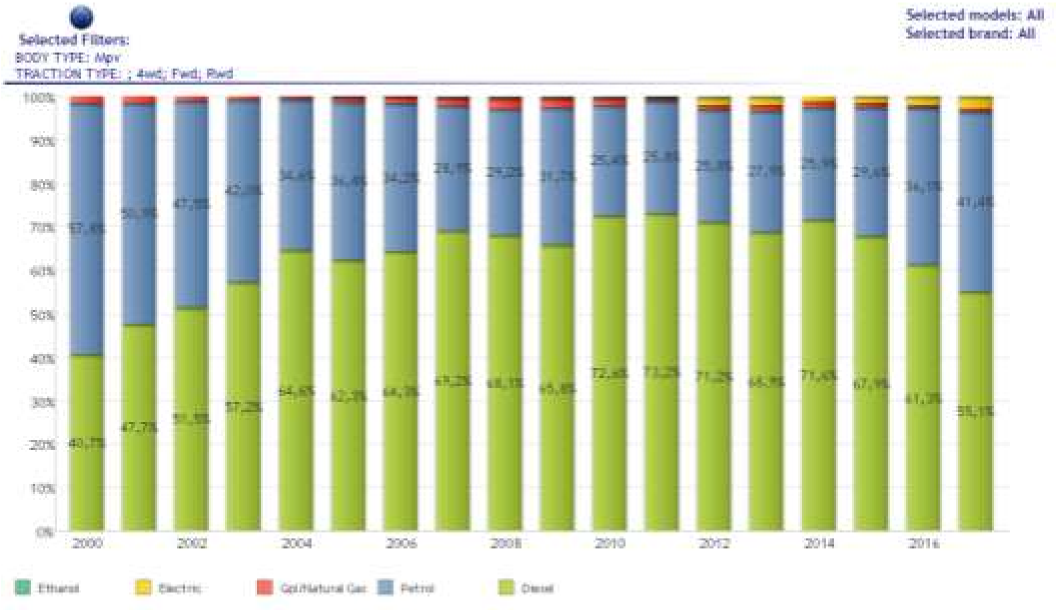


Figure 144: Segment L1 Fuel Mix trend 2000-2017

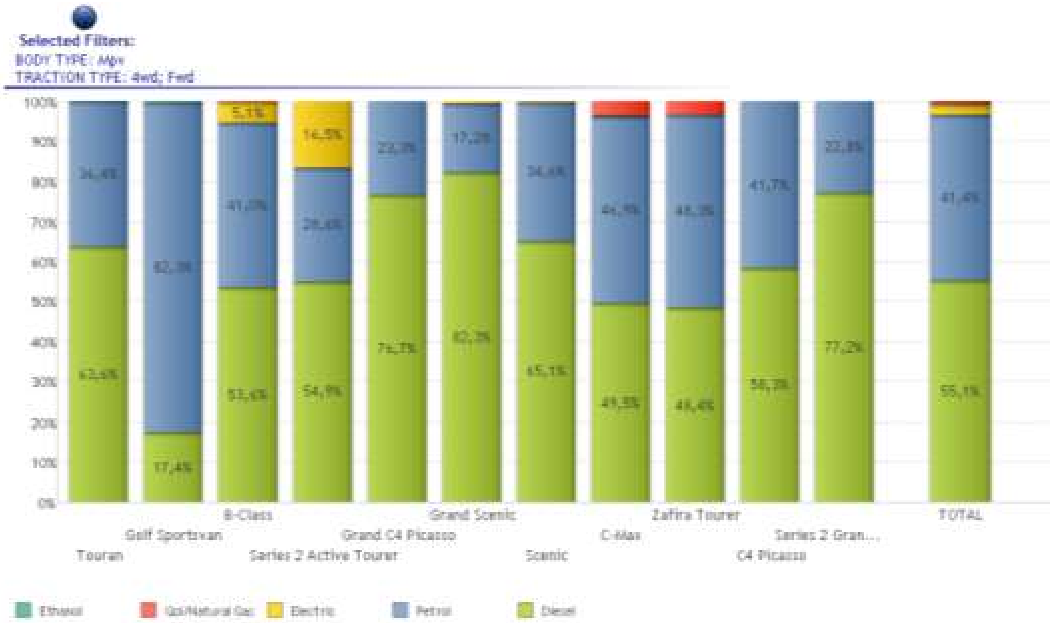


Figure 145: Segment L1 Fuel Mix Fuel Mix H1 2017 Segment

9.2.12 L2 Segment

Diesels play a major role in L2 segment, where still today there are some models sold exclusively with diesels engines. A little decrease has been registered but the quote is still up to 89%.

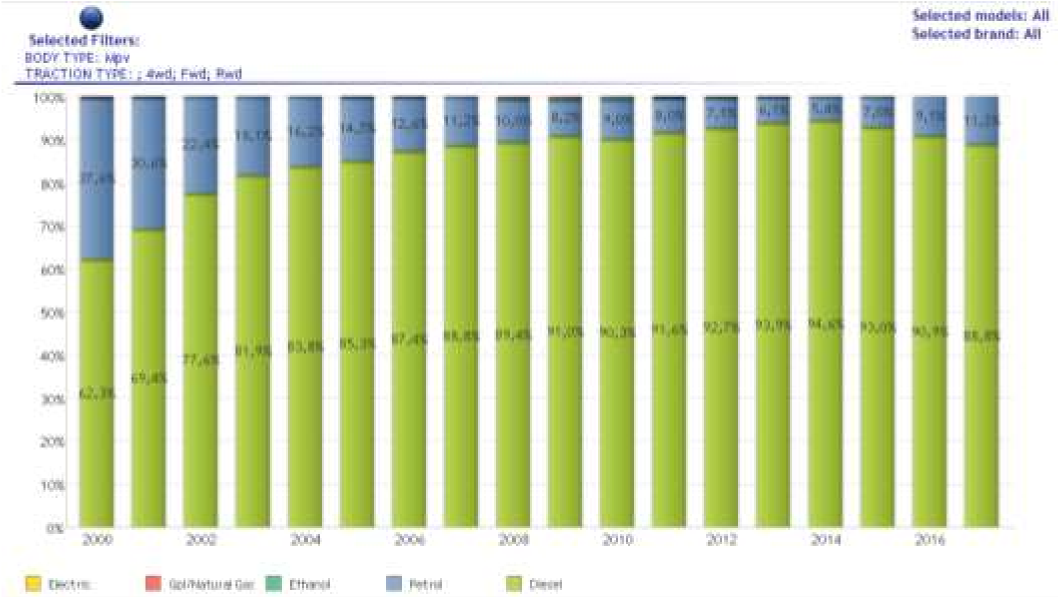


Figure 146: Segment L2 Fuel Mix trend 2000-2017

Figure 147: Segment L2 Fuel Mix Fuel Mix H1 2017 Segment

9.2.13 P Segment

Small minivans are still sold mainly with diesel engines but the trend is decisively negative. Big cities block of diesels are going to affect the choices of workers that use the car for transportation of goods in the urban areas. The best seller in France and UK have already shifted towards petrol.

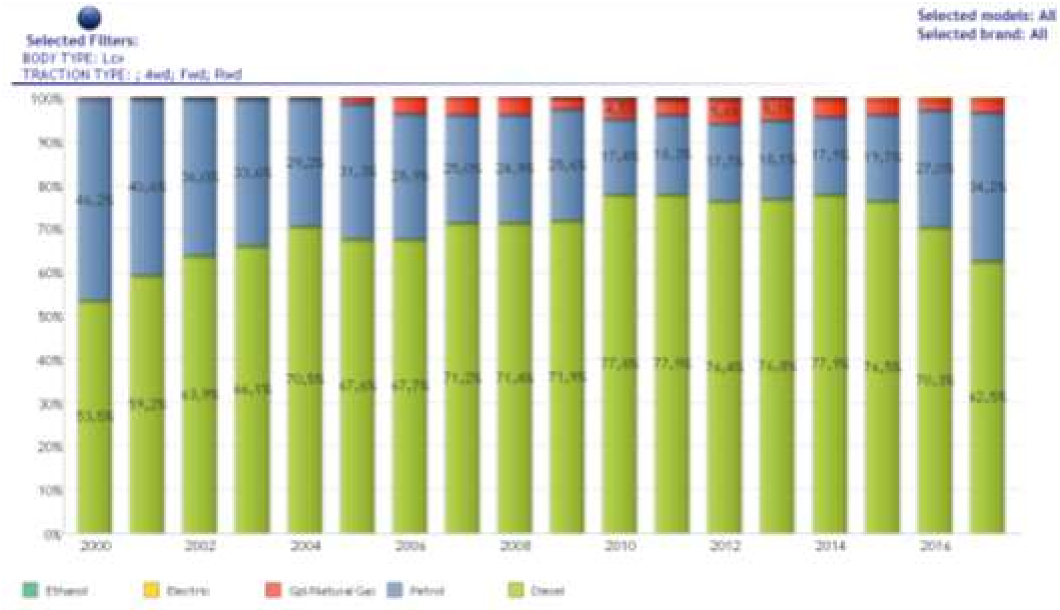


Figure 148: Segment P Fuel Mix trend 2000-2017

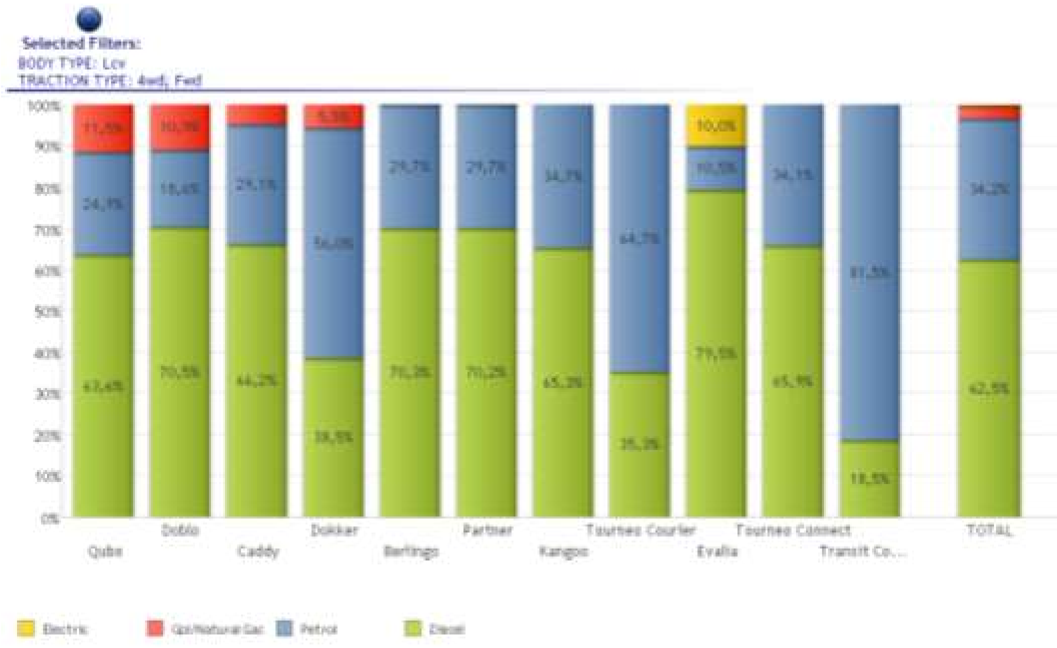


Figure 149: Segment P Fuel Mix Fuel Mix H1 2017 Segment

9.2.14 G Segment

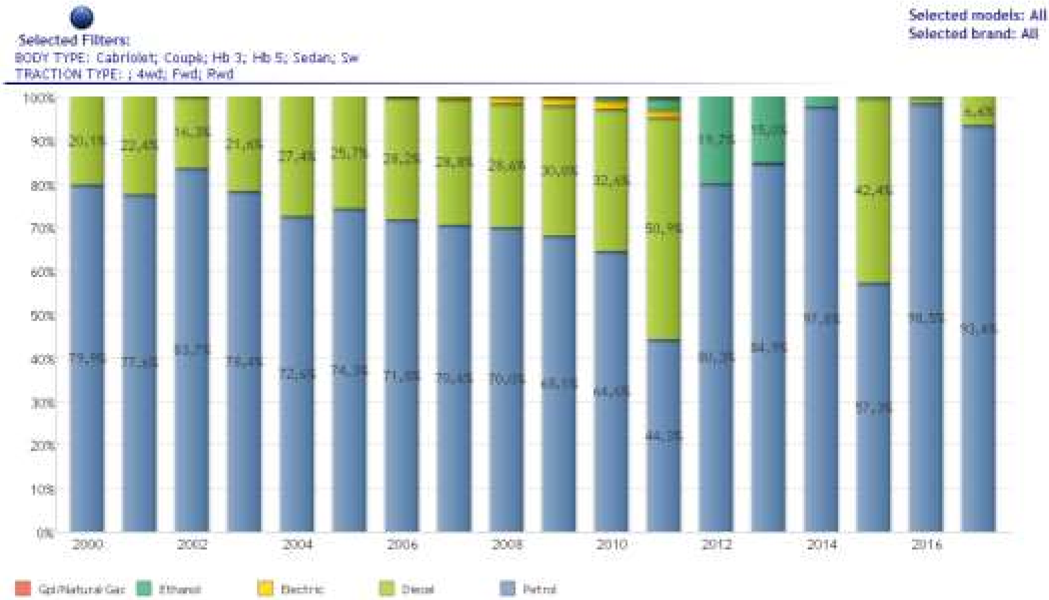


Figure 150: Segment G Fuel Mix trend 2000-2017

9.2.15 H Segment

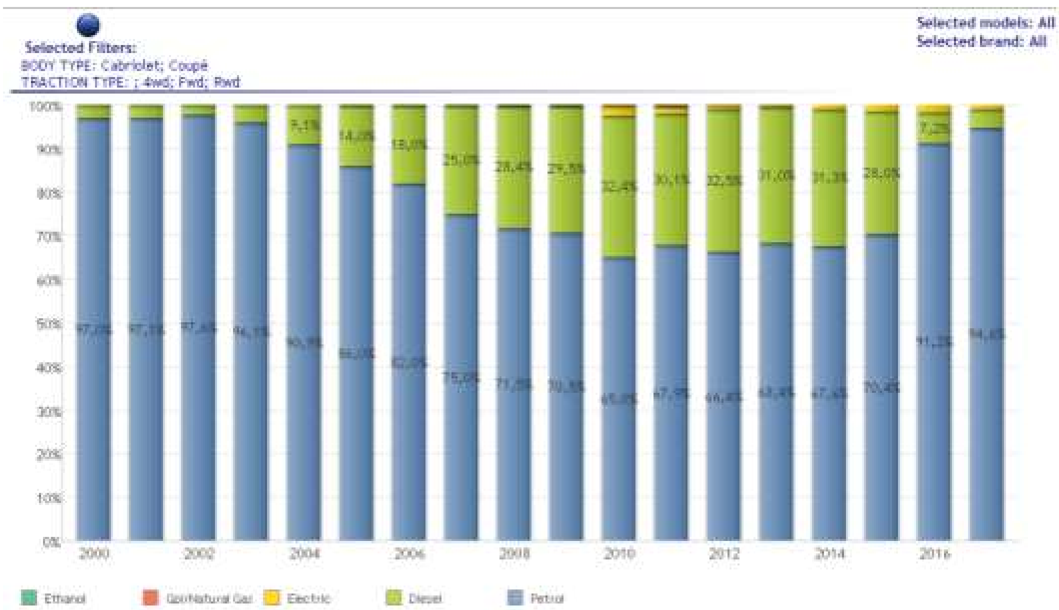


Figure 151: Segment H Fuel Mix trend 2000-2017

9.3 Market Share Evolution of Diesel by Countries.

Table 25 shows the market share of Diesel fueled car registered among new immatricoltion in the country of the European Union in the last 6 years.
The record value of Diesel market share in the whole Eu was registered in 2011 with 56,1%. As far as 2016, the quote has gone under 50%.

	2010	2011	2012	2013	2014	2015	2016
AUSTRIA	50,7	54,6	56,4	56,7	56,8	58,3	57,3
BELGIUM	75,9	75,3	68,8	64,8	61,9	59,7	52,0
DENMARK	45,7	46,7	39,5	32,0	31,7	31,0	36,0
FINLAND	41,5	42,0	38,2	36,8	38,9	35,7	33,3
FRANCE	70,8	72,4	72,9	67,0	63,9	57,2	52,1
GERMANY	41,9	47,1	48,1	47,4	47,8	47,7	45,8
GREECE	4,0	10,0	40,0	57,9	63,5	63,2	55,1
IRELAND	62,2	70,0	73,1	72,0	73,2	71,0	70,0
ITALY	45,9	55,2	53,1	53,9	54,9	55,2	57,0
LUXEMBOURG	75,2	76,7	76,1	73,4	72,0	70,4	65,0
NETHERLANDS	20,0	28,3	28,2	24,8	27,1	28,9	18,9
PORTUGAL	67,1	69,6	70,5	72,3	71,2	68,1	65,1
SPAIN	70,6	70,3	68,9	66,3	64,9	62,7	56,9
SWEDEN	50,9	61,4	66,8	61,5	58,9	57,7	51,5
UNITED KINGDOM	46,1	50,6	50,8	49,8	50,1	48,4	47,7
EUROPEAN UNION (15)	52,0	56,1	55,6	53,8	53,6	52,1	49,9
ICELAND	21,7	42,3	50,1	51,0	49,2	46,7	44,7
NORWAY	74,9	75,7	64,2	52,5	48,7	40,8	30,8
SWITZERLAND	30,2	32,7	37,1	37,0	37,0	38,7	39,6
EFTA	43,6	45,7	45,2	42,1	40,9	39,6	37,0
WEST. EUROPE	51,8	55,7	55,2	53,3	53,1	51,6	49,5

Table 25: M.S of Diesel in EU Countries

Source: Association Auxiliaire de l'Automobile (AAA)

Diesel remains the preferred fuel type of European, but the situation is different in every specific country: Scandinavia and Netherlands register the lowest number, while Ireland, Portugal and Luxembourg the highest. The difference is quite big, ranging from 18,9% in Netherlands to 70% in Ireland, as highlited in Figure 152. Politicals actions and incentives for green cars made the difference in the formers, while the economical running cost advantages of diesels were a decisional factors for the latters.

From a deeper analysis of the five major markets, that accounts for most of the car immatricolations in Eu, Diesels has grown strongly until the economical crysys of 2008, that represented the first big drop since 1990.

After a step recover, in the following years, the trend was inverted with strong effect in France and Spain, thw two most diesel-dependent countries. Only Italy showed a different behaviour, with Diesel quote slowly increasing over the years.

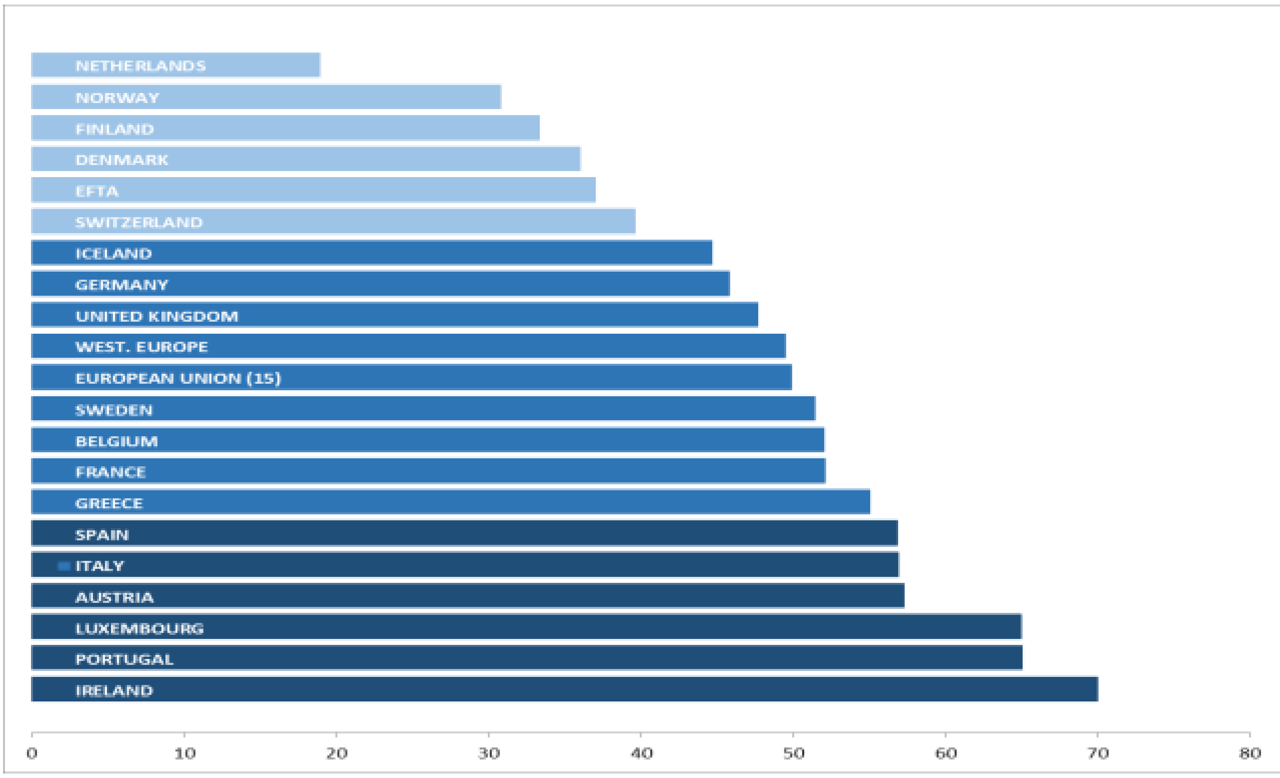


Figure 152: EU country ranked by Diesel M.S.

Source: Association Auxiliaire de l'Automobile (AAA)

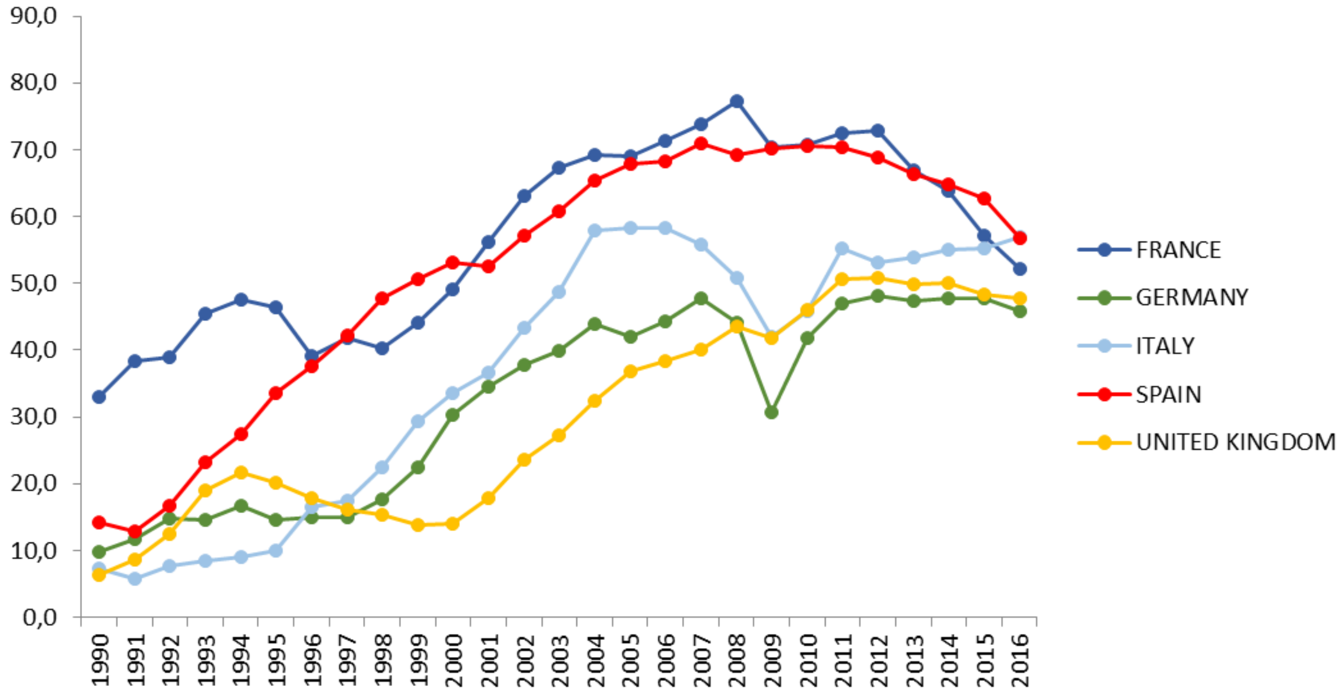


Figure 153: Trends of Diesel M.S. in 5 EU MM

Source: Association Auxiliaire de l'Automobile (AAA)

9.4 Market Share Evolution of Diesel by manufacturers

In Europe car manufacturers are still strongly dependent on diesel engines, as shown in Figure 154.

As far as 2016, Volvo sells 83% of its vehicles equipped with CI engines, followed by the triad of German premium brands, all above 70% of mix. Also the French manufacturers are above 50%, endorsing the strong influence of Germany and France in EU.

On the other side, Toyota's decision to cut off investments on Diesel in spite of hybrids led the quote down to only 15%, the smallest among the big players.

Fiat, Seat and Opel follow slightly above 30%, dragged by the influence of segment A and B among their offers.

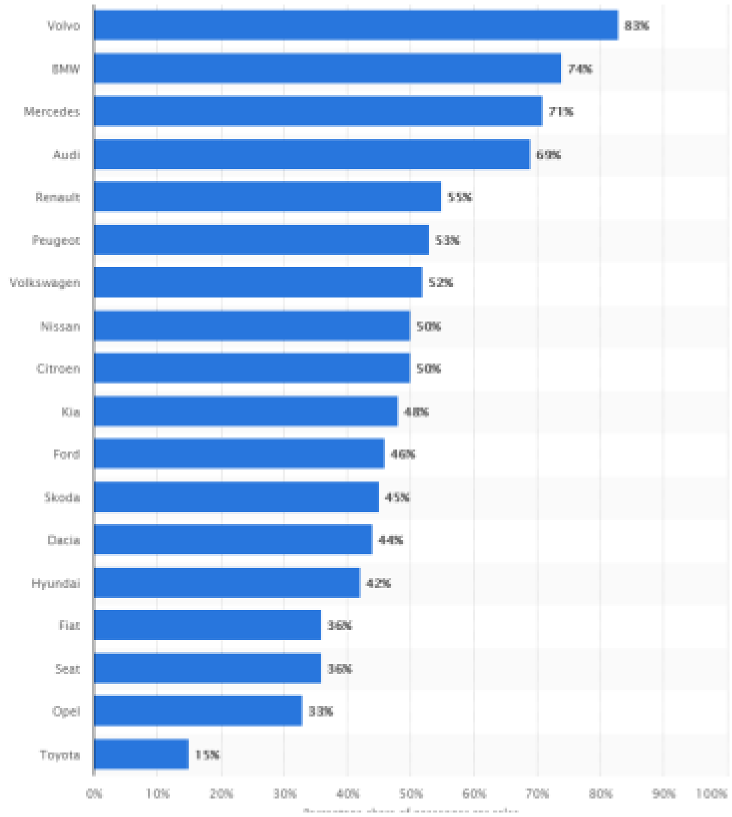


Figure 154: Manufacturers ranking by M.S. of Diesel engines.

Source: Statista 2018

10. FINAL CONSIDERATIONS

As stated in the previous chapter, the consequent decline of market share of diesel vehicles in EU has just started and the future perspectives seem to be not rosy.
Worldwide, diesel market share is projected to fall to 4 percent by 2025 from 13.5 percent today according to a December 2016 report by UBS Group.
Manufacturers are conscious of this big change and are already adopting new investments' policies to be able to offer competitive models in the years to come.

10.1 EV's and Hybridizations Programs

Many efforts are being implemented on the search of alternative powertrains, such as hybrids and electric, but also fuel cells in a broader prospective.
Those are some of the official announcements made by big manufacturers concerning millionaire investments in research.

- In 2017 Volkswagen announced that it would attempt to bring 30 or more BEVs to market by 2025, with a target of 2 million to 3 million sold by that year, roughly 25 percent of its total sales. This year, the company upped the ante again, vowing to create electric versions of all 300 of its models. After its diesel scandal debacle, Volkswagen is all in on electrics.
- In March 2017, Daimler Mercedes-Benz announced that it was accelerating its EV program and would have 10 new EVs to market by 2022.
- In July 2017, Volvo announced that all its models introduced in 2019 and after would be hybrid or electric.
- BMW just announced that by 2025 it would have 12 new BEVs and 13 new hybrids on the road.
- Jaguar Land Rover just announced that all of its new models from 2020 onward would be hybrid or electric.
- Nissan Renault Group is the first big company to have effectively provided the markets with EV's models. Even if the first attempts (Renault Fluence, Renault Zoe, Nissan Leaf), didn't prove successful as hoped, the Leaf is the most sold Full Electric Car in the world and has just been updated with the 2nd generation, that promises the lower costs and higher performances.
- And of course there are big electric car companies like Tesla and Faraday Future which plan to sell 100 percent BEVs now and forever.

According to OPEC (Organization of the Petroleum Exporting Countries), the forecast for the sales of electric vehicles in the world are more than positive. The sales are going to reach the milestone of 100 million cars by 2032.

The most important driver in this evolution is the cost of batteries: in 2010, li-on battery packs were $1,000 per kilowatt-hour. Today they're under $300. By 2026, BNEF expects them to be under $100, and under $73 by 2030. That's just through scale and learning, not any particular technological leaps.

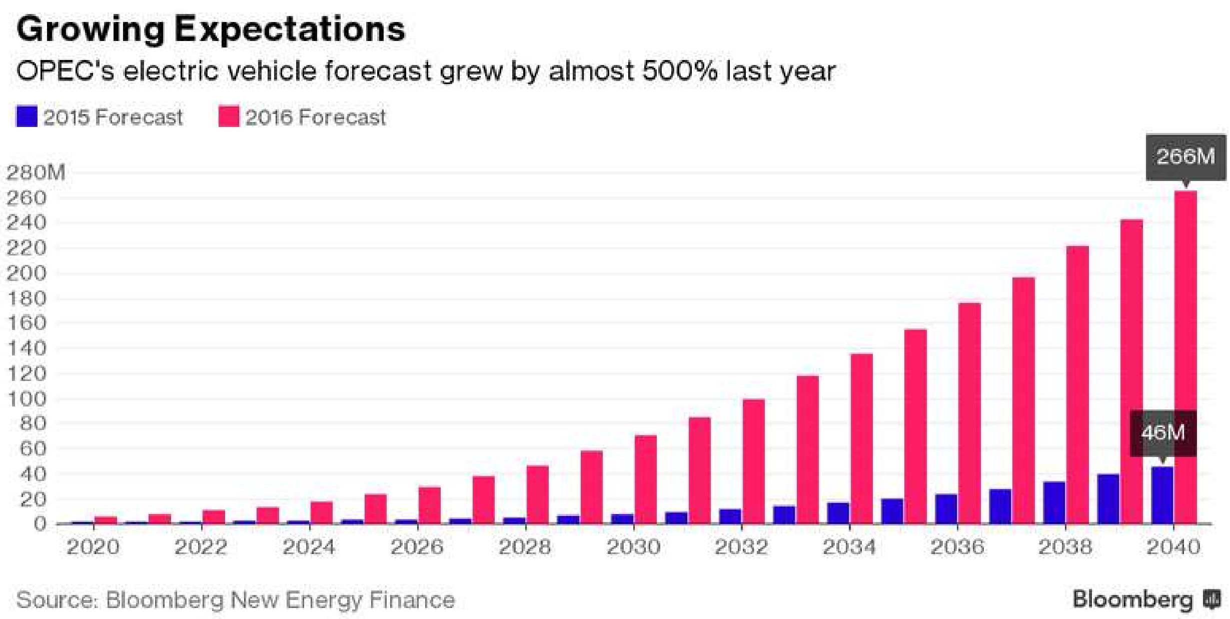


Figure 155: Electric vehicle forecast growth

10.1.1 The environmental impact of electric cars

Even if EVs offer advantages in terms of powertrain efficiency, maintenance requirements, and zero tailpipe emissions, the last of which contributes to reducing urban air pollution relative to conventional internal combustion engine vehicles, thinking of EVs as the perfect green solution is misleading.

According to the results of the study "*Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles" by Troy R. Hawkins, Bhawna Singh, Guillaume Majeau-Bettez, and Anders Hammer Strømman"* EVs powered cars offer a 10% to 24% decrease in global warming potential (GWP) relative to conventional diesel or gasoline vehicles assuming lifetimes of 150,000 km.

On the counterpart, taking into account the whole Life Cycle (vehicle production, use, and end of life together with all relevant supply chains) **EVs exhibit the potential for significant increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion impacts**, largely emanating from the vehicle supply chain. Results are sensitive to assumptions regarding electricity source, use phase of energy consumption, vehicle lifetime, and battery replacement schedules.

Because production impacts are more significant for EVs than conventional vehicles, assuming a vehicle lifetime of 200,000 km exaggerates the GWP benefits of EVs to 27% to 29% relative to gasoline vehicles or 17% to 20% relative to diesel. An assumption of 100,000 km decreases the benefit of EVs to 9% to 14% with respect to gasoline vehicles and results in impacts indistinguishable from those of a diesel vehicle. Improving the environmental profile of EVs requires engagement around reducing vehicle production supply chain impacts and promoting clean electricity sources in decision making regarding electricity infrastructure.

Nowadays it is counterproductive to promote EVs in regions where electricity is produced from oil, coal, and lignite combustion. The electrification of transportation should be accompanied by a sharpened policy focus with regard to life cycle management.

For cleaner, renewable, and less carbon-intensive energy sources, such as wind energy, these benefits are intensified and accompanied by gains in terms of GWP and FDP. Wind power electricity would allow electric transportation with life cycle carbon footprints as low as 106 g CO_2-eq/km. On the other hand, the use of electricity from lignite combustion leads to a life cycle GWP of 352 g CO_2-eq/km, significantly worse than the comparable ICEV performance. The use of electricity from natural gas combustion seems to constitute the break-even point for EVs relative to diesel ICEVs in terms of GWP. However, human and water toxicities along with metal depletion potentials are always greater for electric transportation independent of the electricity source.

In Figure 156 are represented the normalized impacts of vehicle production. Results for each impact category have been normalized to the largest total impact. Global warming (GWP), terrestrial acidification (TAP), particulate matter formation (PMFP), photochemical oxidation formation (POFP), human toxicity (HTP), freshwater eco-toxicity (FETP), terrestrial eco-toxicity (TETP), freshwater eutrophication (FEP), mineral resource depletion (MDP), fossil resource depletion (FDP), internal combustion engine vehicle (ICEV), electric vehicle (EV), lithium iron phosphate (LiFePO4), lithium nickel cobalt manganese (LiNCM), coal (C), natural gas (NG), European electricity mix (Euro).

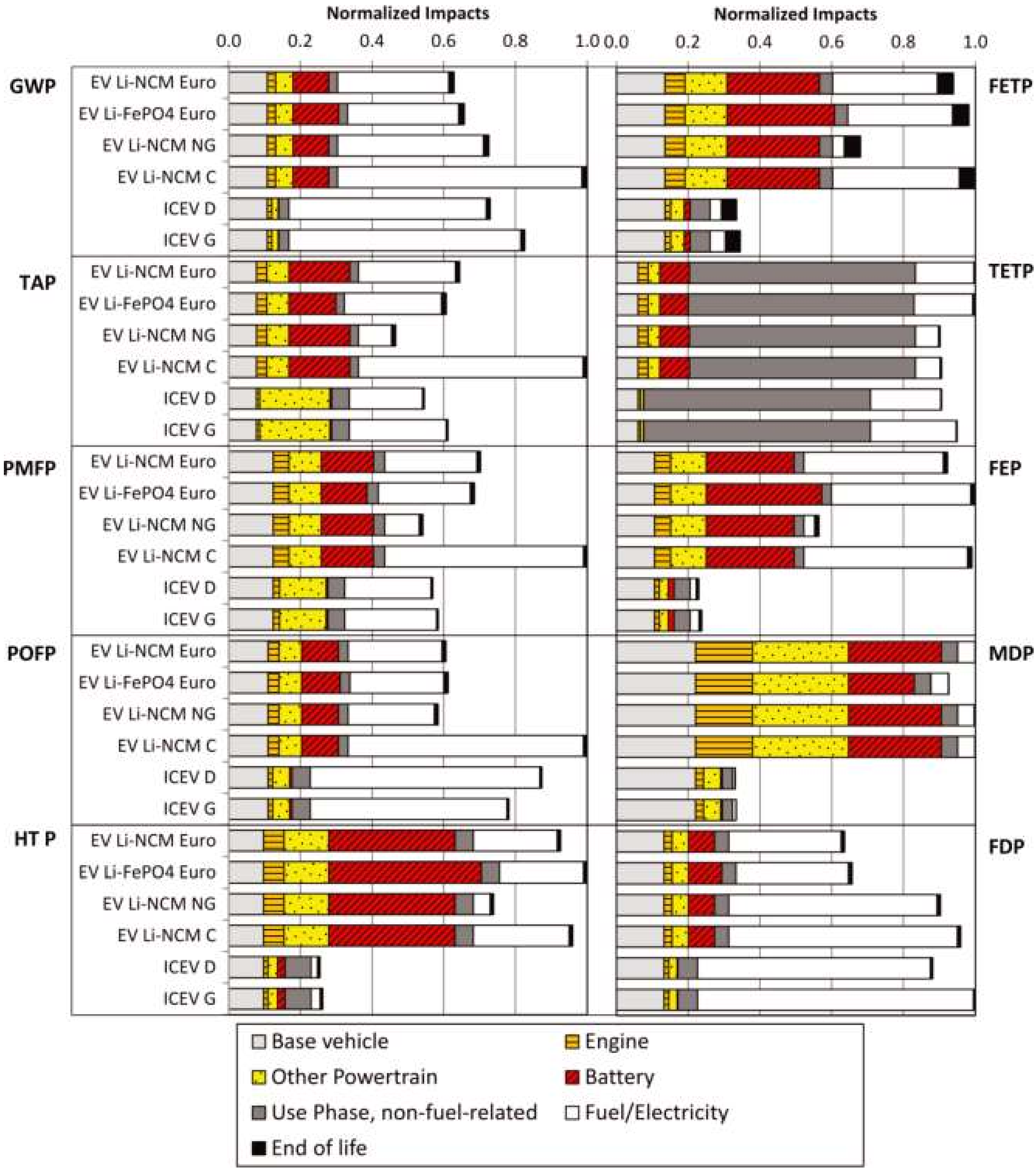


Figure 156: Impact of vehicle production

10.2 United States

In the United States, diesels have never conquered the petrol dominated market. The effect of Dieselgate has had a catastrophic impact on the investments concerning this kind of technology:
Diesel's future has been relegated back to what it was about 20 years ago, an engine choice for pickup trucks.
The lower cost of petrol, compared to EU, is not putting diesel in a competitive position compared to the situation in Europe, where taxation has always helped the former.

Just 28,604 diesels were sold in the U.S. in the first four months of 2017, down 35 percent from the prior-year period. Automakers are also offering fewer diesel models in the U.S. than they were just two years ago, in large part due to growing demands from regulators.
Only nine diesel models were available from five auto brands for the 2017 model year in the U.S, according to the EPA, that compares to 22 models from 8 brands in model year 2015.
Much of the decline in sales and choice stems from the scandal at Volkswagen AG, which was forced to pulled 12 diesel models sold by its Audi, Porsche and namesake VW brand off the market.
That was a big change in strategy for VW, which had invested heavily in diesel. From 2009 through 2015, Volkswagen made high-torque, fuel-sipping "clean diesel" engines a pillar of its U.S. brand identity, deploying them widely across its line-up as a fun-to-drive alternative to sluggish gasoline-electric hybrids.
That strategy has been all but abandoned in the wake of its emissions scandal. The company won't offer new diesel models through at least the 2018 model year and if VW eventually does bring diesels stateside once again, company executives have said the engines are unlikely to be used as widely as before.

After VW admitted cheating, the EPA began subjecting all diesel passenger cars to a new battery of tests designed to ensure there was no other wrongdoing elsewhere in the industry.
The agency has since now not yet certified conformity of Fiat Chrysler's diesel Jeep Grand Cherokee and Ram 1500 pickup variants to U.S. tailpipe rules following talks with the company to resolve the issues.
Daimler had been working for months to get its diesels approved by EPA, but put that process on hold as the 2017 model year enters its final months. While there was hope the diesel engines would eventually return, Mercedes research and development boss Ola Källenius recently put that idea to rest. Speaking to The Detroit Bureau, Källenius said the company's latest diesel engine has significantly reduced emissions but he believes there simply isn't enough demand to justify bringing it to the United States.

"The diesel doesn't fit into our portfolio in the U.S, as diesel-powered vehicles only accounted for about three percent of the company's sales in their best year. In 2016, diesel sales were particularly low as they accounted for less than one percent of the company's overall sales"

There are manufacturers that, on the other side, are still offering or planning to introduce new diesel cars in the next months:

General Motors offers five diesel models: one passenger car (the Chevrolet Cruze), two crossover utilities (Chevy Equinox and GMC Terrain), and two mid-size pickup trucks (Chevrolet Colorado and GMC Canyon).
Jaguar Land Rover has two passenger sedans, its compact XE and mid-size XF, and the Jaguar F-Pace and Range Rover Velar certified with its 2.0-litre turbodiesel-4 engine

It's worth noting that **BMW,** the sole German maker on the EPA list, still offers the diesel 328d passenger car in three configurations and the X5 xDrive 35d crossover utility vehicle this year.
A BMW executive recently confirmed the return of a X3 diesel powered, but there's no word on which engine will be offered in the model. There's no word on when the X3 diesel will go on sale but it will likely arrive sometime after the 540d xDrive which is hit dealerships in February.

Car and Drivers reported a diesel-powered **Kia** Sorento will be launched in the United States early next year. The news was confirmed by Kia Motors America's vice president of product planning who told the publication the company is working with the EPA to get the diesel engine approved for sale.
Orth Hedrick declined to say which engine the company is trying to have certified but the publication believes it could be the 2.2-litre turbodiesel four-cylinder that is offered in the European crossover.

While the EPA booklet lists two **Mazda** diesel models as certified (the Mazda 6 sedan and CX-5 compact crossover)those have yet to reach the market.

"We can't comment on specific timing quite yet, but we continue to work with the EPA and California, and will make an announcement as soon as possible."

Figure 155 is the official 2018 EPA's Fuel Economy Guide Model Year 2018 list of Diesel cars that can be sold in the USA nowadays. It is clear that the reduced number of alternatives available is the direct consequence of institutional decisions not to support widespread of diesel in the country.

Manufacturer Model Configuration (trans, eng size, cyl)	MPG Comb	MPG City/Hwy	Annual Fuel Cost	GHG Rating	Notes
COMPACT CARS					
BMW					
328d					
A-S8, 2.0L, 4cyl	36	31/43	$1,250	7	D T
328d xDrive					
A-S8, 2.0L, 4cyl	34	30/40	$1,350	6	D T
CHEVROLET					
Cruze					
A-9, 1.6L, 4cyl	37	31/47	$1,250	7	D T
M-6, 1.6L, 4cyl	37	30/52	$1,250	7	D T
JAGUAR					
XE					
A-S8, 2.0L, 4cyl	36	32/42	$1,250	7	D T SS
XE AWD					
A-S8, 2.0L, 4cyl	34	30/40	$1,350	7	D T SS
MIDSIZE CARS					
BMW					
540d xDrive					
A-S8, 3.0L, 6cyl	30	26/36	$1,500	5	D T SS
CHEVROLET					
Cruze Hatchback					
A-9, 1.6L, 4cyl	35	30/45	$1,300	7	D T
M-6, 1.6L, 4cyl	35	29/48	$1,300	7	D T
JAGUAR					
XF					
A-S8, 2.0L, 4cyl	35	31/42	$1,300	7	D T SS
XF AWD					
A-S8, 2.0L, 4cyl	34	30/40	$1,350	7	D T SS
MAZDA					
6					
A-S6, 2.2L, 4cyl	NA	NA	NA	NA	
SMALL STATION WAGONS					
BMW					
328d xDrive Sports Wagon					
A-S8, 2.0L, 4cyl	34	30/40	$1,350	6	D T
SMALL PICKUP TRUCKS 2WD					
CHEVROLET					
Colorado 2WD					
A-6, 2.8L, 4cyl	25	22/30	$1,800	4	D T
GMC					
Canyon 2WD					
A-6, 2.8L, 4cyl	25	22/30	$1,800	4	D T
SMALL PICKUP TRUCKS 4WD					
CHEVROLET					
Colorado 4WD					
A-6, 2.8L, 4cyl	23	20/28	$2,000	4	D T
Colorado ZR2 4WD					
A-6, 2.8L, 4cyl	20	19/22	$2,250	3	D T
GMC					
Canyon 4WD					
A-6, 2.8L, 4cyl	23	20/28	$2,000	4	D T
STANDARD PICKUP TRUCKS 2WD					
RAM					
1500 2WD					
A-8, 3.0L, 6cyl	23	20/27	$2,000	4	D T
1500 4x2 HFE					
A-8, 3.0L, 6cyl	NA	NA	NA	NA	
STANDARD PICKUP TRUCKS 4WD					
RAM					
1500 4WD					
A-8, 3.0L, 6cyl	22	19/27	$2,050	3	D T
SMALL SPORT UTILITY VEHICLES 2WD					
CHEVROLET					
Equinox FWD					
A-6, 1.6L, 4cyl	32	28/39	$1,400	6	D T SS
GMC					
Terrain FWD					
A-6, 1.6L, 4cyl	32	28/39	$1,400	6	D T SS
SMALL SPORT UTILITY VEHICLES 4WD					
CHEVROLET					
Equinox AWD					
A-6, 1.6L, 4cyl	32	28/38	$1,400	6	D T SS
GMC					
Terrain AWD					
A-6, 1.6L, 4cyl	32	28/38	$1,400	6	D T SS
JAGUAR					
F-Pace					
A-S8, 2.0L, 4cyl	29	26/33	$1,550	5	D T SS
LAND ROVER					
Range Rover Velar					
A-S8, 2.0L, 4cyl	28	26/30	$1,600	5	D T SS
MAZDA					
CX-5					
S6, 2.2L, 4cyl	NA	NA	NA	NA	
STANDARD SPORT UTILITY VEHICLES 4WD					
BMW					
X5 xDrive 35d					
A-S8, 3.0L, 6cyl	25	23/29	$1,800	4	D T SS

Figure 157: List of Diesel Cars homologated in 2018 in the USA up to date

Nevertheless, as opposite of EU, the price of Diesel is actually higher than the one of Petrol**.** The higher refinement costs are not compensated by a favourable taxation.

These considerations make clear that Diesel for Light Veichles transportation in the USA has not a positive outcome for the future. The market is gonna shrink even more pushed by policies towards the electrification of the fleets.

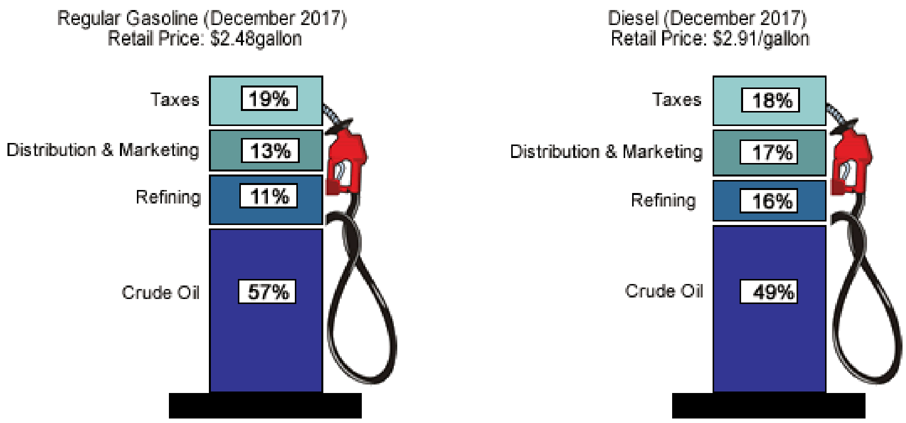


Figure 158: Prices of Petrol and Diesel in the USA

Source: U.S. Energy Information Administration

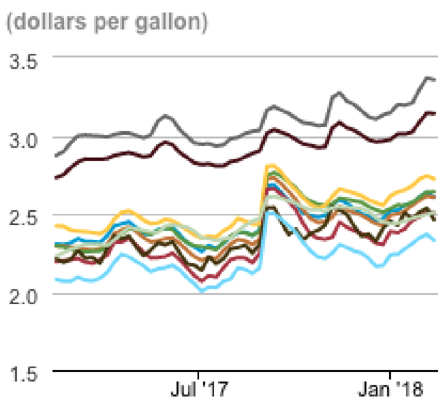


Figure 160: Trend of prices of Petrol in the USA

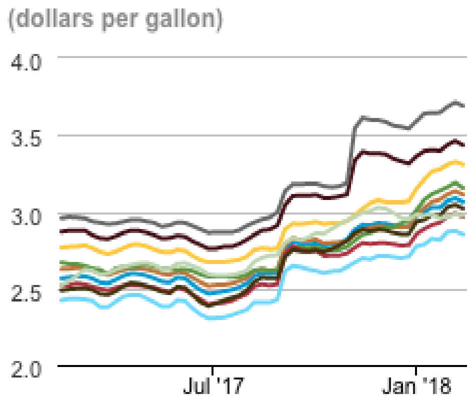


Figure 159: Trend of prices of Diesel in the USA

10.3 Europe

Concerning Europe (the continent which diesels future depends on), the situation is much different and not so easily predictable. Given the above news about limitations of internal combustion powered cars in the main cities, many manufacturers are already changing their future outcome perspectives.
One point is clear, the first step of the transition is going to take place throughout an hybridization of the current manufacturers fleets. By 2020 every manufacturer will have to offer some electrified models in order to lower the average CO2 emissions and avoid economical penalties.

10.3.1 EU 2030 Forecast

The global car market is continously growing, with new sales expected to rise at an annual average of 2.8% from 2015 to 2023. Mastering the greatest change that the industry has experienced in the past hundred years through technological developments and challenges by connectivity, autonomous driving, and digitization of the value chain is the only way to take advantage of that growth.
According to the consultant agency, Alix Partners, in 2030, half of all cars are expected to have an electric or hybrid powertrain, and almost all cars will be connected. To achieve that, the automotive supply chain will undergo large-scale changes, and systematic digitization will reduce the structural costs by a quarter. Online services will heavily influence the driving experience and offer crucial new revenue opportunities. In cities, individual mobility through free-float car sharing will continue to grow. And only organizations that integrate that new world into their strategies will be able to compete and stay relevant in this rapidly evolving industry. Up to date, many companies have already started with their own direct commitment in the car-sharing business with strategic partnerships. BMW with DriveNow, Dailmer with Car2Go, Fiat with Enjoy.
The forecast of powertrain’s mix in Figure 161, takes into account that although cars can meet near-future emissions standards by way of diesel and petrol engines, the cost of emissions reduction technologies will increase significantly. By 2030, if the same purchasing incentives exist, consumers will not see any noticeable differences between the price of a traditionally powered vehicle and a fully electric one. That’s the reason why market mix of Diesel is predicted to fall drastically to 9% in 2030. During the next 15 years, the study predicts a progressively increasing proportion of battery-powered electric vehicles, plug-in hybrids, and mild hybrids with 48-volt technology. Such vehicles are predicted to represent 35 to 40% of all new car sales by 2025, increasing to more than 65% in 2030. Those gains will be at the detriment of the diesel engine, which is expected to completely lose its cost advantages in small and medium vehicles and hence market share by 2030. Alternative drivetrains will require investments of more than 40 billion euros by 2020 by the German auto industry alone, according to the VDA, the country's

auto association, making the push to reducing carbon emissions the greatest challenge facing automakers.

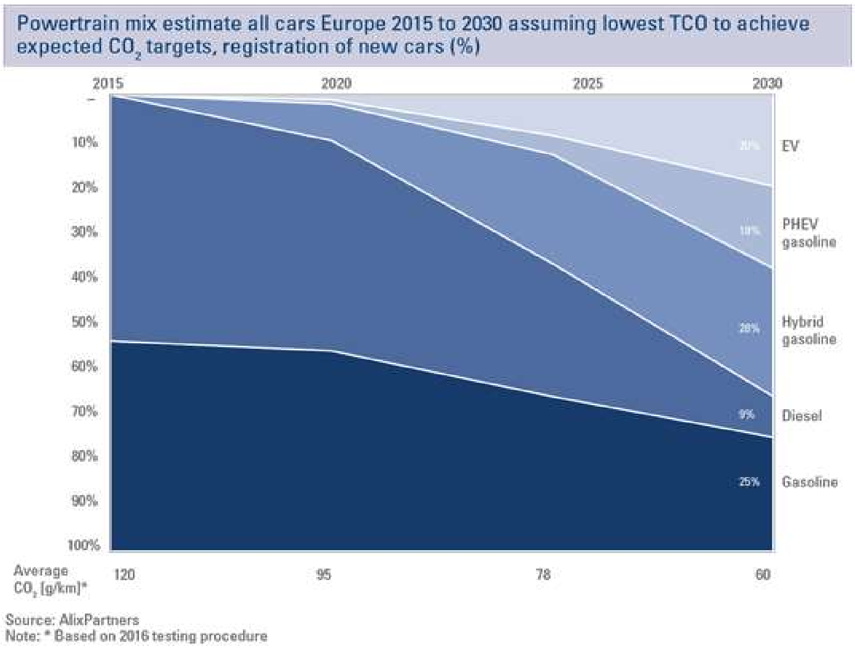


Figure 161: Overall trends in fuel mix 2015-2030

TCO: Total Cost of Ownership

The road in not easy though. As battery-powered electric vehicles grow in prominence, focus will shift to improving the global charging infrastructure. In such cities as London, for example, around 75% of households do not have off-street parking, and a robust public charging infrastructure will be critical. The study calculates by 2030 a global demand for more than 300 million charging stations in the 488 cities around the world with populations of more than one million, which represents an investment of €3.7 trillion.

The major gain is going to be achieved by hybrids, that for the next 10 years represent the biggest compromise between the pro and cons of both Petrol and Full Electric. With no need of dedicated infrastructures and direct charging (plug-in excluded), hybrids can drastically reduce fuel consumption is city driving, and, as a consequence, emissions.

Hybrids, on the other side, are being developed mainly coupled with petrol engines, that could better fit the continous stop and start of the ICE in discountinous driving. Former attempt of coupling an electric motor with a Diesel engine (that on paper is the best solution, with the advantages of the former in low speed driving and the advantages of the latter in sustained speed ones, like motorways) didn't proove succesful. First and foremost is the issue of cost. On average, a diesel engine costs about 15 percent more to manufacture than a gasoline engine of equal output. Add to that the $1,000 or more for a high-voltage battery pack, power electronics,

and one or two electric motor-generators, and the final outcome is a very pricey powertrain indeed.
There are already some diesel hybrids on the market in Europe but only one of them pairs the diesel engine and electric motor together into a single powertrain: the Mercedes-Benz E 300 BlueTEC Hybrid. Mercedes is the only manufacturer to have already announced investments for diesel hybrids in the next years. The other two, the Peugeot 3008 HYbrid4 and the Citroën DS5 Hybrid are "through-the-road hybrids," meaning that they have one powertrain on either end. Those two can use the electric motor alone for lower-speed trips, the diesel engine for high-speed travel, and combine for highest performance driving by transmitting power through all four wheels. Unfortunatly none of the former solutions met the interest of customers, mainly because of the price, raising a serious question concerning their future.
Renault instead is following a different rute, implementing a Mild Hybrid 48V, called SED-Hybrid Assist, to its 1.5 dci 110hp engines that equips Scenic and Megane. The electric motor “helps” the diesel one in all those unfavoraboule conditions, like the start from standstill, allowing it to turn off for slightly longer periods compared to a traditional start&stop, resulting in a efficiency increase of 8-10%.

Nowadays the roads followed by different manufacturers are different but investments and researches are addresses to find simple and effective alternatives. **Mazda** has just announced a petrol engine capable of working like a Diesel (Skyactive-X), providing the same efficiency with the pros of the petrol fuels.
Toyota instead has already put a stop in diesel, strong of 20 years of researches on hybrids, that led to the capability of offering hybrids with a price surplus almost equal to diesel, thanks also to incentives for clients that want to change their diesel engine, as stated in Figure 162. The same directions is being followed by **Hyundai** and **Kia**, that are slowly hybridizing their fleet.
Also Porsche, directly affected by the dieselgate, has just announced the stop of production of its diesel alternatives.
Germans manufacturers, instead, are following a different trend. In Italy and Germany **VW** group are pushing CNG for all its brands, starting an advertisement campaign that took the place of the previous ones about TDI. **BMW** and **Mercedes** instead are still relying on their diesel, offering discounts for people that change their old diesel for the new more efficient ones.

Also **Fiat** sees a big opportunity in the CNG market, that represents for the present and the near future a feasible and sustainable alternative to both Petrol and Diesel.
On average CNG emits 20% less CO2 compared to an equivalent petrol (making the choice desirable to reach 2020 emissions’ target), and countries like Italy and Germany are adopting policies towards an increase of the distribution system, which is today one of the biggest obstacle to its widespread: in October 2017, the Italian government supervised an important contract between Snam (Società Nazionale Metanodotti), Fiat and Iveco to increase the actual distribution

network of 200% with the objective of triplicate the circulating park in the country above 3 million units.
During the Geneva Auto Show 2018, Sergio Marchionne talked about the topic of Diesel: "*Since there was the Dieselgate scandal, sales decreased in Europe. The costs will be too high to maintain this production. We will reduce dependence on this sector in the future: we have no choice ".* The statement made clear that future investments will move towards different kind of motorizations, even if they won't give up diesels in short terms.

Figure 162: Advertisement incentives, Italy, February 2018.

10.3 Conclusion.

Thus, taken for granted that this work was not supposed to be presented as an apology of the Diesel but as an awareness of the ineluctable destiny, where is Diesel going to?
From a mere consumer point of view, Diesel is still, in most cases, the most cost efficient alternative on the market. Excluding models offered with LPG and CNG, that have a lower cost per km, Diesels are preferred by costumers in spite of their slightly higher price compared to Petrol.
The turning point is: *how many kilometers do I have to run every year to compensate the acquisition cost and start to save money?*
This is the fundamental question diesels' future is depending on. Up to date, the total amount of Kms that represents the Break-Even Point between Petrol and Diesel falls in a variable range on average inbetween 50.000 and 100.000 kilometers.
Taking into account that in Italy, the average distance traveled is about 11.500 kilometers per year, 5 to 10 years are needed to completely absorb the delta price of a diesel engines.

Therefore, is evident that the solution to the question is a mere issue of costs. The new and more demanding emissions regulations are pushing manufacturers to invest in technologies to reduce pollutants' emission, but at which economical expenses?
Statistically the price step needed for a Diesel engine in every update of the Euro normative is continuously increasing. According to the Financial Times, the economical effort asked for the development of new engines, along with the updated technology, will pull the prices of diesel towards an increase of 20% on a statistical average, mining the feasibility of the investments themselves: how many customers will be disposed to actually pay for that?
Anyhow, technologies described in Chapter 4 proved to be successful in reducing the level of pollutants: tests confirmed that a 2016 3.0-litre BMW 5-Series, one of the lowest polluting diesel cars available on the market today, emits just 23 milligrams of NOx per kilometer, which is less than a third of the legal limit of 80mg/km. Whereas the 2016 petrol-powered Renault Kadjar 1.2-litre model was found to emit 130mg/km, which is six times greater than the BMW. Taking into account the UK market, the cleanest 10 percent of new diesel cars emit an average of 70mg of NOx per kilometer, way less than the average petrol ones.

As stated in the analysis by segment in Chapter 9, small and economical cars like segment A ones, are no more sold with diesel alternatives, just because the small margins of the segment are not paying back the huge amount of investments needed to provide them with green diesels engines. Nevertheless, a segment A diesel car proved not to be competitive anymore on the market, since its cost were too demanding for the average buyers.

The same effect is slowly affecting also the other segments of the market. Segment B has already started to be subject to the same dynamics: Renault has announced the end of diesels for the new generation of Clio.
Bigger segments can better absorb the costs of diesel yet, as easily inferable by the fuel mixes shown above, but there are visible hints that the trend is slowly changing as well.

Furthermore customers are starting to be concerned also about the future value of their cars, wondering if the present purchase of a diesel is still suitable also in a long term prospective. All the news mentioned above are entering the heads of people more and more often, pushed by newspaper and media, engaging the idea of the unfeasibility of such motorization. As a result, everyday more and more customers, that in the past would have gone straight for the purchase of a diesel engine, are starting to ponder and look at the alternatives in a different way.
The advantages of Diesel will still represent a major driver of choice for all those customers asking for big mileages at sustained speed, torque and constant power, all those customers that form the basket of higher segments. Until there won't be a comparable alternative, and until customers will consider the purchase of this motorization convenient, in the light of mere economical, ethic and practical considerations, a not negligible part of the market will stick to that choice.

It is clear though, that foreboding the survival of Diesel as it is today could be misleading. An alternative solution to completely substitute diesel doesn't exist yet, but the next 5 years are going to be characterized by a coexistence of different alternatives, customized to every segment, that are going to modify the fuel market mix as never happened in the past. Many analysts have already predicted that the further development of alternative power propulsion systems (methane, hybrid, electrics, hydrogen..), as a consequence of the shift of investments discussed above, will be the final blow to the existence of Diesel.
This very thin correlation between customer demand, technological feasibility and institutional decisions, is what put the question mark to a question worth billions of euros, since none of this three variables has found unanimity among its players.
However, like in almost every market, the final choice is always going to be in the hand of the clients according to their "reasons to buy", and, as generally acquainted, that is the most unpredictable variable.

Those perspectives, along with the announced forced stops of circulation by the institutions in all the major cities, are the reasons why all the common thought is that we have just experienced the swan song of the Diesel, the song of a swan that is irreversibly flying towards its final last sunset.

11. SOURCES

- *Internal Combustion Engine Fundamentals, John B.LHeywood*
- *The Motor Car, G. Genta*
- *The Autocar (Thirteenth edition, circa 1935) Autocar Handbook, London: Iliffe & Sons.*
- *EUROPEAN VEHICLE MARKET STATISTICS Pocketbook 2017/18, International Council on Clean Transportation Europe*
- *Diesel, Rudolf (October 28, 1897). "Diesel's Rational Heat Motor: A Lecture". Progressive Age Publishing Company. Retrieved October 28, 2017*
- *"Diesel Car" (Future Publishing Limited, July edition, 1993), p.104*
- *United Nations ECE/TRANS/WP.29/GRPE/2016/3, Economic and Social Council; "World Forum for Harmonization of Vehicle Regulations. Working Party on Pollution and Energy"; seventy second session, Geneva 12-15 January 2016.*
- *In-Use Emissions Testing of Light-Duty Diesel Vehicles in the United States, Dr. Gregory J. Thompson, May 15, 2014*
- *EEA Report No 27/2016 Monitoring CO2 emissions from new passenger cars and vans in 2016*
- *2 "US EPA, Fuel Economy Guide Web Site," Available at http://www.fueleconomy.gov, Last updated: March 17, (2014).*
- *6 "Control of Air Pollution From New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulphur Control Requirements; Final Rule," US Environmental Protection Agency, Federal Register Vol. 65, No. 28, pp. 6698 - 6870, February 10th, (2000).*
- *Peltz, James F.; Masunaga, Samantha (25 October 2016).* "The largest auto-scandal settlement in U.S history was just approved. VW buybacks begin next week". *Los Angeles Times. Associated Press*. Retrieved 26 October 2016.
- *Lewis, Michael (28 June 2016).* "Volkswagen agrees to landmark $15.3-billion emissions settlement in U.S". *Toronto Star*. Retrieved 29 June 2016.
- "Volkswagen/Audi Diesel Emissions Settlement Program". *Volkswagen/Audi Diesel Emissions Settlement Program. US: Volkswagen*. Retrieved 1 July 2016.

- *VW owners in US to get up to $10,000 in emissions deal".* BBC News*. UK. 28 June 2016. Retrieved 1 July 2016.*
- *Kottasova, Ivana.* "Volkswagen emission cheating costs Qatar $5 billion". *CNNMoney*. Retrieved 28 September 2015.
- "VW urged to come clean over which UK diesel vehicles are affected"*, The Guardian, Para 11*, retrieved 29 September 2015
- *Loehr, Julia,* "Two-thirds of Germans still trust Volkswagen after emissions scandal"*, The Guardian*, retrieved 21 October 2015
- *Hennessy, Julie (9 October 2015),* "VW Messed Up, But the Emissions Scandal won't Turn off Customers", Fortune, retrieved 11 October 2015
- *Isidore, Chris.* "Volkswagen sold 3,060 diesels in US last month before scandal"*. CNNMoney*. Retrieved 3 October 2015*.*
- *Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles" by Troy R. Hawkins, Bhawna Singh, Guillaume Majeau-Bettez, and Anders Hammer Strømman*
- *Notes of the course "Combustion Engines" by prof. Mittica*
- *http://www.dieselduck.info/historical/01%20diesel%20engine/rudolph_diesel.html#.Wiv88LSdWRt*
- *http://www.deutsches-museum.de/en/collections/machines/power-engines/combustion-engines/*
- *https://www.dieselnet.com/tech/diesel_history.php#diesel*
- *http://www.themomentmagazine.com/history/features-history/perkins-peterborough/*
- *http://www.automostory.com/first-diesel-car.htm*
- *https://en.wikipedia.org/wiki/Fractional_distillation#/media/File:Crude_Oil_Distillation.png*
- *https://chembloggreen1.wordpress.com/2012/12/20/65/#comments*
- *http://mechteacher.com/diesel-cycle/#ixzz50ruVzLUE*
- *http://airqualityontario.com/science/pollutants/carbon.php*
- *https://fortress.wa.gov/ecy/publications/documents/0002008.pdf*

- *https://www.rac.co.uk/drive/advice/know-how/euro-emissions-standards/*
- *https://www.dieselnet.com/standards/cycles/ece_eudc.php*
- *https://www.auto.it*
- *http://wltpfacts.eu/what-is-wltp-how-will-it-work/*
- *https://www.dieselnet.com/standards/cycles/wltp.php*
- *http://ec.europa.eu/eurostat/statistics-explained/index.php/Europe_2020_indicators_-_climate_change_and_energy*
- *https://www.eea.europa.eu/highlights/co2-emissions-from-cars-and*
- *https://www.nytimes.com/interactive/2015/business/international/vw-diesel-emissions-scandal-explained.html*
- *https://www.nytimes.com/2018/01/25/world/europe/volkswagen-diesel-emissions-monkeys.html*
- *https://www.japantimes.co.jp/news/2016/05/16/business/corporate-business/nissan-sucked-into-car-emissions-scandal-as-south-korea-alleges-fraud/#.WnMmRq7ia00*
- *http://carsalesbase.com/us-car-sales-data/*
- *https://www.statista.com/statistics/425324/eu-car-sales-share-of-diesel-engines-by-brand/*
- *http://money.cnn.com/2017/09/11/autos/countries-banning-diesel-gas-cars/index.html*
- *https://www.thelocal.de/20160118/stuttgarters-asked-to-stop-driving-as-pollution-hits-new-high*
- *https://www.reuters.com/article/us-germany-emissions/diesel-cars-can-be-banned-from-german-cities-court-rules-idUSKCN1GA2XD*
- *https://nordic.businessinsider.com/tesla-is-the-most-popular-carmaker-in-norway-this-month--/*
- *https://www.theguardian.com/world/2017/sep/11/china-to-ban-production-of-petrol-and-diesel-cars-in-the-near-future*
- *https://www.fueleconomy.gov/feg/pdfs/guides/FEG2018.pdf*
- *https://www.eia.gov/petroleum/gasdiesel/*

- *http://www.earthday.it/Citta-e-trasporti/Gli-italiani-in-automobile-11mila-km-l-anno*
- *https://legacy.alixpartners.com/en/Publications/AllArticles/tabid/635/articleType/ArticleView/articleId/2065/categoryId/21/A-Watershed-Moment-for-the-Automotive-Industry.aspx*