CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

FACULTY OF ENVIRONMENTAL SCIENCES

DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL MODELLING

DIPLOMA THESIS

EMISSIONS FROM COMBUSTION ENGINES OF MODERN CARS AND THE POSSIBILITY OF THEIR FURTHER REDUCTION

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Study program: Landscape Engineering

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DIPLOMA THESIS ASSIGNMENT

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Landscape Engineering
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Thesis title

Emissions from combustion engines of modern cars and the possibility of their further reduction

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Objectives of thesis

This study is generally aimed at analysing emission trends from road transport in the EU with a particular focus on emissions from combustion engines of modern passenger vehicles and the possibilities of their further reduction.
Specific objective:
- Describing the development and the emissions formation from the combustion engines
- Describing the development of vehicle technology for cleaner and more energy-efficient vehicles of a petrol and diesel engines after-treatment
- A holistic, integrative planning approach to environmental and transport policy goals and their effective implementation
- To investigate the standards that the automobiles manufacturers need to follow regarding emission control from the combustion engines
- To investigate the current technology control and measurements of the emissions and if these technologies are sufficient for reaching the EU targets
- To investigate the question what is the best solution that the manufacturers need to follow for emissions reduction.

Methodology

1. Research Questions
2. Location analysis
3. Data Collection
4. Data Analysis and Compilation
5. Barriers

The proposed extent of the thesis

50 pages of text

Keywords
Automobile industry, Combustion engines, Emission, Energy-efficient, COx, NOx, WLTP

Recommended information sources

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I declare that I have worked on my diploma thesis titled " Emissions from Combustion Engines of Modern Cars and the Possibility of their Further Reduction" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any other person.
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ABSTRACT

The aim of the work described in this thesis was to study the development of the current technology of the combustion engines after-treatment, as well as the progress and further possibilities Europe is making towards reducing emissions of personal mobility in modern cars and their successful implementation. This thesis focuses mainly on Europe legislation and their effective implementation and manner that they should be reached. With the European Commission proposal for 2025 and 2030 standards, there is a renewed target on emissions control. Several analyses in this thesis were applied with examples of data collected from various sources to research the progress, trends and the forecast of emissions from road transport. So, in the end, it is shown the best alternative propositions for the further possibility of emissions reduction from modern cars.

Contents:

Prologue

This thesis studies the progress and further possibilities Europe is making towards decarbonizing personal mobility in modern cars. It also presents indicators from a wide range of sources, which show the progress, and many of the underlying trends of the emissions from combustion engines of modern cars and the possibility of their further reduction.

The automobiles are part of our existence, for many years. At the start of the twentieth century, there were more electrical vehicles on the roads than combustion engines cars. They were silent, fast, simple to maintain and convenient to drive. The petrol was considered a lot of being a dissipation than something helpful and was on the market available in pharmacy vendors only. However, later, because of the fast development of combustion engines and the petrochemical industry, and nearly no improvement in battery technology, the cars with combustion engines took over. The growing variety of cars caused harms in our living environment from the emissions of the exhaust fuels of the combustion cars that contribute to pollution. Currently, they are considered as one of the main pollutants in the atmosphere and they are many limitations and prevention practices of the emission reduction that needs to be achieved.

Controlling of the fuelling and of the combustion processes in the engine achieves some reduction of the exhaust emissions. Some advanced systems, as Exhaust Gas Recirculation (EGR), can also further reduce significant level of emissions (under specific operative conditions). An advanced exhaust fuels after-treatment system consisting of catalytic converters traps, and filters, if properly designed could nearly eliminate the emission in most driving conditions. The only technical problem is the operative temperature of the catalysts throughout urban driving, the temperature of the exhaust gases sometimes stays extremely low.
Developing advanced catalytic systems together with advancing the engine, controlling technologies and the fuel, slowly but surely fulfil the expectation of reducing the emission level. Today, it is essential to lower the most crucial emissions – PM (particulate matter), nitrogen oxides and carbon oxides, to make sure sustaining or improving the air quality while increasing the number of vehicles. Nevertheless, it is not enough to line limits only for brand new vehicles - they have to be properly maintained as well. European legislation established requirements for the durability of the emissions systems and obliges holders, to test their vehicle's emissions regularly, as well as automobiles manufactures must test sample vehicles to prove emissions compliance procedure throughout the vehicle lifetime.

Since the Dieselgate scandal broke in September 2015, the automotive industry has been under increased media and regulatory scrutiny for its contribution to the urban air pollution crisis in our cities. From the initial focus on the defeat devices fitted to Volkswagen vehicles sold in the US, the scandal spread globally to almost every company, and every market selling diesel cars. In response, the EU has strengthened regulations, including introduction to a new real-world emissions test - Worldwide Harmonised Light Vehicle Test Procedure (WLTP) a strengthened system for approving cars.

With the European Commission proposal for 2025 and 2030 standards, there is a renewed target on emissions control. This master thesis is focused on the progress of emission control with proposition for further possibilities of emission reduction from the road transport.

Chapter 1.

1. Introduction

The biggest issue of combustion engines are the products of the combustion process.. Carbon dioxide is the most deliberated product, which is a significant greenhouse gas, yet its effects can be reduced by utilizing another fuel (fuel from some renewable sources, carbon-free fuel). Ecologically safe emissions created from the combustion engines are still at the development phase and have not changed much since the last years, or the production of such engines is very expensive. Because of the entrenched fuel industry and little improvements on the battery innovation technology, we still may encounter combustion engines in the following years. However, later on, as there is not much significant improvement on the combustion engines and the goals that manufacturers need to keep up with are becoming more rigorous there is more likely that electrical vehicle will become prevailing. [1]

Some big cities in the USA in the 4th decade of the 20th century have already come across air pollution issues related to the increasing number of vehicles. In the 60s, the quantity of passenger cars started to upsurge rapidly. Then, the exhausting fuels of the passenger cars contained significant quantities of unburned hydrocarbons and additional products of unfinished combustion, such as carbon monoxide, aldehydes, carboxylic acids, and ketones. In the combustion chamber at high temperature and pressure, aerial nitrogen reacts with oxygen to form nitrogen oxides (NO_X). The usual volume of automobile emissions remained: 90 g Carbon monoxide (CO), 15 g hydrocarbons (HC) and 6 g NO_X per mile. Shortly the concentration of these chemicals reached extreme levels, which during a sunny day it was resulting with this photochemical reaction [2]:

$$NO_2+O_2+h_v+M \rightarrow \mathrm{NO}+O_3+M$$

Equation 1-1

- where M is any other present molecule, leading to a formation of high irritant ozone gas.

The only effectivity of combustion engines is under steady operation and at higher load. While transient operation periods the combustion process is harder to regulate, and additional fuel are necessary to shift the operation mode. These disadvantages can be overcome with hybrid drivetrains. Usually, this kind of system consists of one combustion engine, a generator, and at least one electric motor. In hybrid electric vehicles (HEVs), reducing fuel consumption is while the electric motors assist the combustion engine during transient phases. Additionally, the electric system is able to transform the vehicle kinetic energy during braking to electric energy, which can be stored in batteries or capacitors for further use. This kind of hybrid vehicles equipped with this drivetrain is becoming more common and popular in recent days, because of their fuel efficiency (as shown in chapter 6.2).

Electric vehicles (EVs) are silent, produce nearly no pollutants from the exhaust gases. In addition, they do not need complex filtration, lubrication and exhaust gas after-treatment systems needed for combustion engines. The main issue is their short range, long recharging periods and high price. Furthermore, the batteries (usually lithium) necessary for these vehicles are very heavy and high cost. However, electric vehicles slowly gain in acceptance, with slight performance and range improvements, becoming cheaper, making them more accessible to the public. As well as being incredibly cheap to run, electric vehicles are becoming more widely produced, resulting in a slightly drop of the prices.

1.1 Air Pollution – Environmental Impact and History of Modern Transportation

One of the biggest accomplishments of modern technology is the development of inner combustion (IC) motor vehicles. By fulfilling many of the mobility requirements in everyday life, automobiles have made excellent contributions to the development of the modern society. However, the big number of vehicles in use around the globe, created severe environmental and human life issues and continues to cause them. Air pollution, global warming, and as well as the fast depletion of the petroleum resources of the Earth are now major issues of concern.

In latest decades, transport-related research and development activities have highlighted the development of high-efficiency, clean, and safe transport. Typically, it has been suggested that electric vehicles, hybrid electric cars, and fuel cell vehicles will substitute the conventional automobiles in the near future.

Currently, most of the vehicles on the road are inner combustion motor vehicles. Combustion of this vehicles is a fuel-to-air response that releases heat and combustion products. An engine transforms heat into mechanical power and releases the combustion products into the atmosphere. However, the combustion of HC fuel is never ideal in the combustion engines. The combustion products contain, besides carbon dioxide and water, a certain amount of nitrogen oxides (NO_x), carbon monoxides (CO) and unburned HCs, all of which are toxic to human health. [3]

1.2 Main components of the exhaust fuel combustion

Depending on fuel quality and the operating conditions, a combustion engine generates a wide variety of vaporous products. When an engine is powered by fossil fuels, water and carbon dioxide are always the main components:

$$HC(fuel) + O_2 \rightarrow CO_2 + H_2O + work + heat$$

Equation 1-2

Under high pressure and temperature, further significant components are made due to the imperfect burning of the fuel. These are primarily:

• Carbon monoxide (CO). Slightly less dense than air. Extremely toxic dreary without scent and tasteless flammable gas; it is formed throughout the unfinished combustion of the carbon-based fuels. Diesel motors produce altogether less CO than petrol engines. Exposures to carbon monoxide may cause significant damage to the heart and central nervous system.

• Particulate matter (PM). The particulate diameter ranges from nm to μm. Subtypes of PM's include suspended particulate matter (SPM), thoracic and respirable particles, inhalable coarse particles, which are coarse particles with a diameter between 2.5 and 10 micrometres (μm) (PM_{10}), fine particles with a diameter of 2.5 μm or less ($PM_{2.5}$), ultrafine particles, and soot [4]. They have impacts on climate and precipitation that harmfully affect human health. PM is also an issue for direct-injection petrol engines.

• Nitrogen oxides (NO_x) are developed throughout the combustion process with great temperatures by reactions of atmospheric nitrogen with oxygen. Even in low concentrations such as 200 ppm NO_2, Nitrogen oxides can be extremely dangerous and have a fatal consequence. Currently, the legislature regulates the only NO_x as a sum of NO and NO_2.

• Unburned hydrocarbons (UHCs). Emitted after petroleum is burned in an engine. Product of incomplete combustion. UHCs may have cancerogenic effects on the human body.

• Sulphur dioxide (SO_2). Formed throughout the combustion of fuels or lubricants containing Sulphur. It has sturdy terrible outcomes on catalyst activity and binds itself to particulate matter. The formation of Sulphur dioxide is avoided or prevented by using fuels or lubricants with very low Sulphur contents, cf. [5]

• Carbon dioxide (CO_2) is formed throughout the combustion of fuels based on carbon (carbon-based fuels). It is a significant greenhouse gas. The right and the only way for the reduction of its emissions is to limit the use of carbon-based fuels.

• Ammonia (NH_3) is a chemical substance with colourless gas and a characteristic pungent smell. It is classified as an extremely hazardous substance. It is the result of the reduction of nitrogen oxides. With its presence, the nitrogen oxides can be decomposed to nitrogen and water, which is applied in the technology of catalytic reduction (Chapter 3.5.1)

In Table 1.1 are listed the usual components amount of exhaust fuels from modern-day cars powered by combustion engines.

Table 1.1 Usual numbers of various components of exhaust fuels in vol. % [5]

	N_2	CO_2	H_2O	O_2	CO	HC	NO_x	PM
Gasoline	71.20	14.50	12.90	0.30	0.67	0.07	0.21	< 1
Diesel	75.00	6.90	6.30	11.80	0.05	0.02	0.06	< 1

Chapter 2

2. The aims of the thesis

The aim of the work described in this thesis was to study the improvement of the current technology of the combustion engines after-treatment, as well as the progress and further possibilities Europe is making towards reducing emissions of personal mobility in modern cars and their successful implementation. Several technologies have been introduced in the last couple of years, which made gradual improvement in the field of exhaust fuels after-treatment. As mentioned before, some fuel components produced by combustion engines are harmful and may cause damage to the living environment. In order to ensure the improvement in this field industrial states and commissions implemented strengthened legislation, including the announcement of a new real-world emissions test (WLTP) a strengthened system for approving cars. These legislations define standards, which the carmaker companies need to follow in order to be accepted to sell and run their vehicles on the market. This thesis focuses mainly on Europe legislation and their effective implementation and manner that they should be reach. With the European Commission proposal for 2025 and 2030 standards, there is a renewed target on emissions control and possibilities of their further reduction from modern cars and this master thesis is focused on some of those.

The study objectives include:

- Describing the development and the emissions formation from the combustion engines
- Describing the development of vehicle technology for cleaner and more energy-efficient vehicles of a petrol and diesel engines after-treatment
- A holistic, integrative planning approach to environmental and transport policy goals and their effective implementation
- To investigate the standards that the automobiles manufacturers needs to follow regarding emission control from the combustion engines
- To investigate the current technology control and measurements of the emissions and if these technologies are sufficient for reaching the EU targets
- To investigate the question what is the best solution that the manufacturers need to follow for emissions reduction.

Organization of the thesis and experimental approaches

The thesis is structured into 7 chapters, which aim to cover various aspects of emissions from the modern cars. ***Chapter 1*** provides a comprehensive review of the status of combustion engines of the modern-day vehicles, including a brief introduction of the combustion process and its products, air pollution – environmental impact and history of modern transportation, and exhaust gasses created from the combustion engines. The main part of this chapter summarizes the by-product of the exhaust gasses.
Chapter 3 provides a literature research and a useful overview of the current knowledge in the field of exhaust fuels after-treatment legislations in Europe and the development of the emissions from the combustion engines, as well as development of vehicle technology for cleaner and more energy-efficient vehicles. It synthesizes knowledge of the problem dealt with, compare various points of view, as well as evaluate and contrast the approach of different authors. This Chapter explains the current state of emissions control technology from the

combustion engines in EU such as catalysts and filters components where all components have to work together to obtain maximum emission reduction.

Chapter 4 describes strategies and approaches of various data collection, data analysis methods for emission trends from road transport in the EU, with a particular focus on emissions from road transport and modern passenger vehicles. Moreover, characterize background materials used so that the reader can assess the significance of the background materials that were used for the analyses.

Chapter 5 describes the current emission state from road transport and progress towards the better air quality in Europe. However, the recent state of emission control technology from combustion engines in the EU (mentioned in Chapter 3.5) cannot significantly reach the current and the future targets that European Commission is proposing so as a result a shift to electro-mobility or other alternatives are needed such as hybrid engines and biofuels. Possible variants for further reduction and better technologies are discussed in ***Chapter 6***.

A general discussion and perspectives are provided in ***Chapter** 7*.

Chapter 3

3. Emissions formation and emissions after-treatment from the combustion engines

3.1. Emissions formation

The primary principle of the combustion engine remains for more than a hundred years the same. A lot of work has been implemented to improve the usual efficiency of the engines; however, their operation is still not entirely clean. This chapter describes the conditions in the combustion engines, where eventually leads to the formation of “unwanted” by-products and their current control and reduction.

3.1.1. Processes in the work cycle

In Figure 3.1 is shown a thermodynamic cycle of a spark-ignition petrol engine. The ultimate Otto work cycle is divided into these phases, cf. Figure 3.1 (2):

• Adiabatic compression of the gas
• An isochoric feed of heat Q_H – ignition and combustion
• Adiabatic expansion
• An isochoric drain of heat Q_C

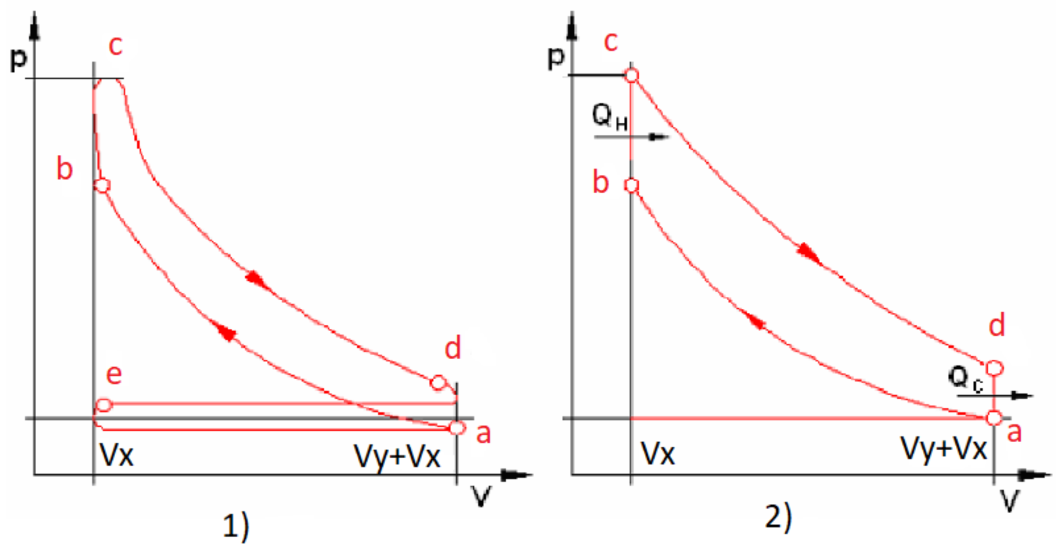


Figure 3.1: Real (1) and ideal (2) thermodynamic cycle of a petrol spark - ignition engine [6].

The work required for compression of the gases from initial volume $v_y + v_x$ to v_x is specified by the area below the curve a-b. The work done throughout expansion from volume v_x to the initial volume $v_y + v_x$ is specified by the area below the curve c-d. The usable work Wu is specified by the area limited by the curves a-b, b-c, c-d and d-a (d-e-a containing losses for real thermodynamic cycle Fig. 3.1 (1). The thermodynamic cycle of a Diesel compression-ignition engine is given in Figure 3.2. The ideal compression-ignition work cycle is split into these phases, cf. Figure 3.2 (2):

• a-b: Adiabatic compression of the gas
• b-c: Isochoric feed of heat Q_{hi}
• c-d: Isobaric feed of heat Q_{hc}
• d-e: Adiabatic expansion
• e-a: Isochoric drain of heat Q_c

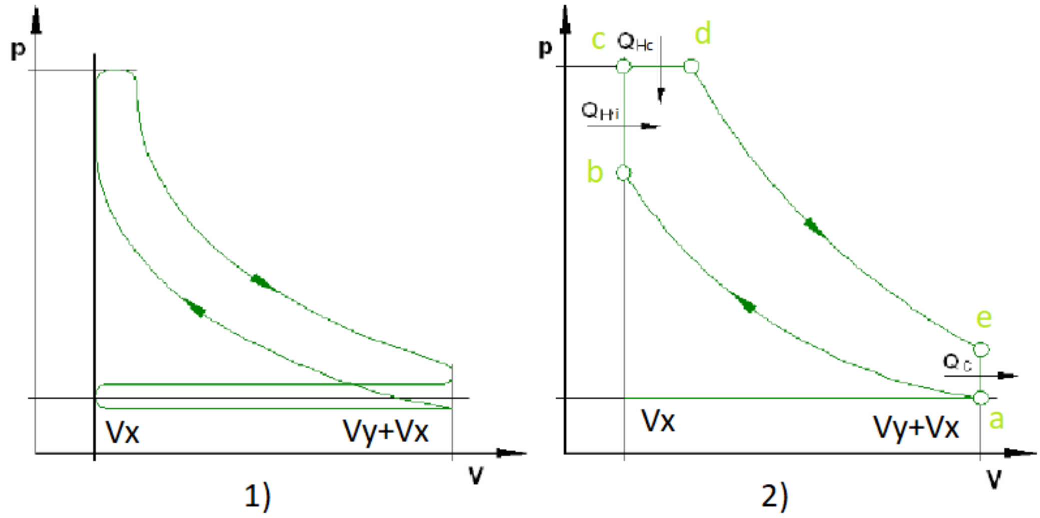


Figure 3.2: Real (1) and ideal (2) thermodynamic cycle of a Diesel – powered compression- ignition engine [6].

The work needed for compression of the gases from initial volume $v_y + v_x$ to v_x is specified by the area below the curve a-b. The work done throughout expansion from volume V_X to the initial volume $v_y + v_x$ is specified by the area below the curve c-d-e. The usable work Wu is specified by the area limited by the curves a-b, b-c, c-d, d-e and e-a, cf. Figure 3.2. The most significant reasons and differences why the real cycle differs from the ideal one is: [7]

• There is incomplete fuel combustion
• There are hydraulic losses throughout suction and exhaust
• It occurs heat exchange among the cylinder walls and the gas
• Combustion does not occur in a constant volume
• There are other gases from the previous cycle in the cylinder

3.1.2 Air-fuel mixture

The combustion engine transfers chemically bond energy to heat, and therefore the generated heat is then converted via the pressure changes into mechanical energy (as described in Section 3.1.1). A proper and suitable air-fuel mixture needs to be prepared in order to efficiently generate heat. When the distribution of the mixture is homogeneous, an air-fuel mixture can be usually perfectly combusted. However, a perfectly homogeneous mixture cannot be prepared for some particular technical reasons. Table 3.2 describes the values of the air excess coefficient in different mixture conditions. [7]

Table 3.2: Values of the air excess coefficient λ.

Condition	Value of λ
Stoichiometric mixture	1.0
Excess of air (lean mixture)	> 1.0
Excess of fuel (rich mixture)	< 1.0
Ignitable mixture (spark-ignition engine)	0.5-1.6
Lower border of smoke (compression-ignition engine)	1.3

The mixture condition is an important parameter to regulate the engine power output. However, regulating the mixture condition is not always relevant – suitable condition needs to be chosen depending on the engine construction.

3.1.2.1 Quantitative power output control

A standard petrol indirect-injection engine works with the homogenized mixture. The most effective conditions for petrol combustion are accomplished with the stoichiometric mixture. This indicates that the fuel quantity is given by the quantity of air. The quantity of the fuel mixture necessary to get the specified power output is then given by determining the quantity of intake air, into which the corresponding quantity of fuel is injected. The mixture condition is controlled by a detector referred to as λ -sensor. A valve within the intake pipes controls the intake airflow. This principle of regulation, unfortunately, causes hydraulic losses, and so the engine potency decreases with decreasing demand on power output (this ends up with enlarged fuel consumption).
The losses may be down by applying a sophisticated regulation system like supercharging and/or variable valve timing (VVT) (Atkinson-cycle or Miller-cycle).
By employing a conventional three-way catalyst, the emissions generated by the engine running in stoichiometric mode can be easily removed. However, diesel engines do not use quantitative control.
Figure 3.3. explain the effect of the air-fuel mixture condition on the parameters of a petrol engine. Terminology is used in the diagrams:

CO, CO_2, NO_x, HC, O_2………… emission compound concentration
p…………………………………...specific power output (kW/dm^3)
be………………………………… specific fuel consumption (g/kWh)

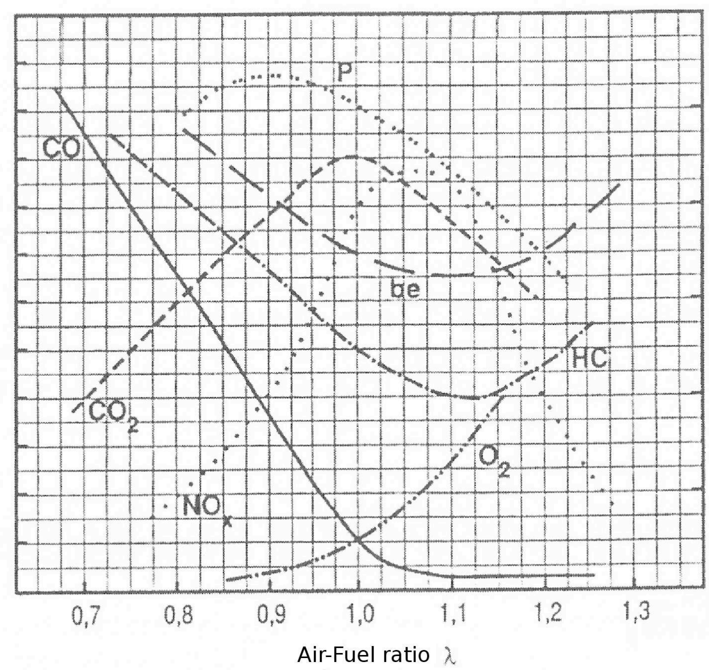


Figure 3.3: Effect of air-fuel mixture condition on the parameters of a petrol engine. [7]

The emissions generated by a petrol engine in stoichiometric mode are removed within the three-way catalyst. In Figure 3.4 are shown the most harmful components which are eliminated with the three-way catalyst (TWC).

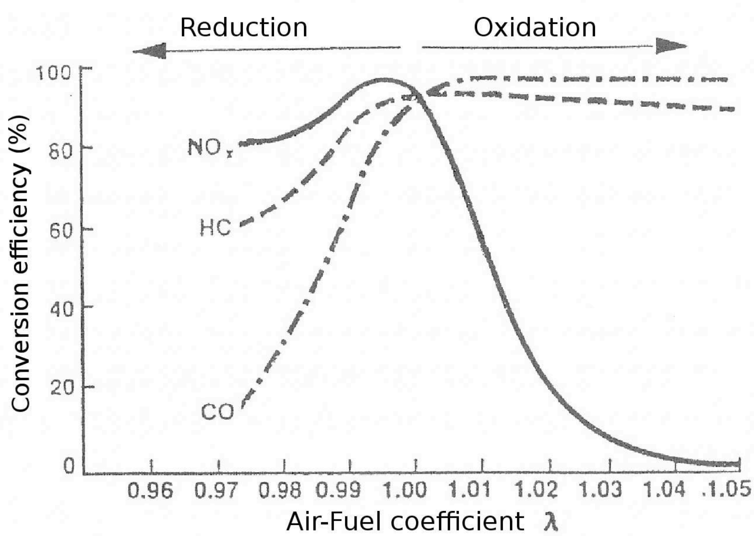


Figure 3.4: Elimination efficiency of a three-way catalyst in dependence of λ for the most harmful chemical components [7]

Under the operating range, the stoichiometric air-fuel mixture ratio cannot be maintained.
Significant enrichment of the mixture is applied when the engine is started, throughout the warm-up phase of the engine, and under full load as well. The emission level outside the stoichiometric area is undesirably high. In order to lower the emission level below the high conditions, secondary air should be blown-in into the system to oxidize the unburned carbon monoxide and hydrocarbons. This includes a positive impact on the catalyst temperature – the catalyst can heat up additionally quickly and reach its optimal operating temperature. Extreme

mixture enhancement might result in condensation of the fuel on the walls of the pipes (mostly when cold started). Warming the mixture up reduces the obligation of the enhancement. Engines equipped with a mechanical device such as carburettor have installed heating of the intake pipes. Engines equipped with injection systems use similar techniques as the engines with carburettors, and here the fuel will be heated directly (for instance, by injecting the fuel on a heated plate, Figure 3.5).

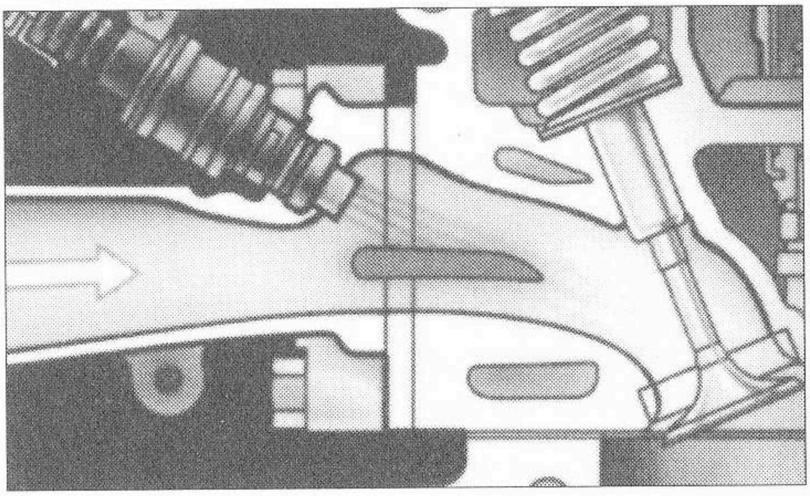


Figure 3.5: *Heating of the injected fuel in an indirect-injection petrol engine.* [7]

An additional crucial parameter of the petrol engine is the interelectrode gap of the cylinder (spark plug). (cf. Figure 3.6).

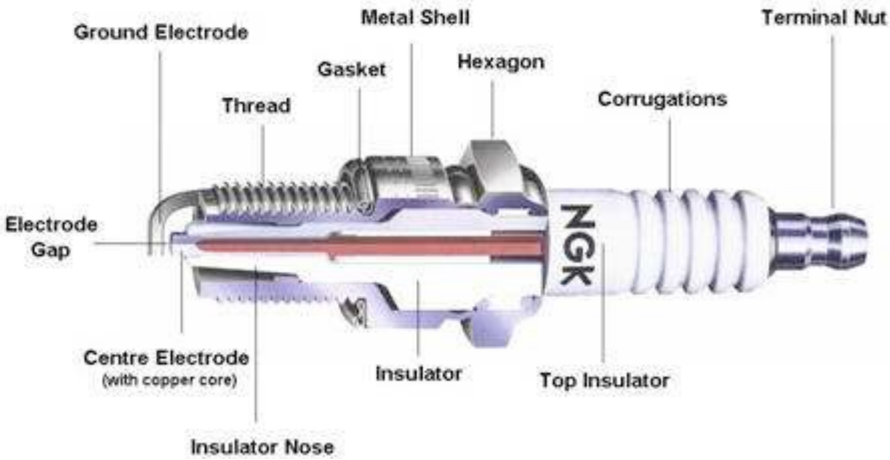


Figure 3.6: Conventional spark plug (cylinder) used in petrol engines. [7]

Increasing the interelectrode gap shifts the minimum of specific fuel consumption and unburned hydrocarbon emissions towards to lean mixture condition. Increasing the spark duration length reduces the emissions and significant reduction of fuel consumption can be achieved, cf. Figure 3.7.

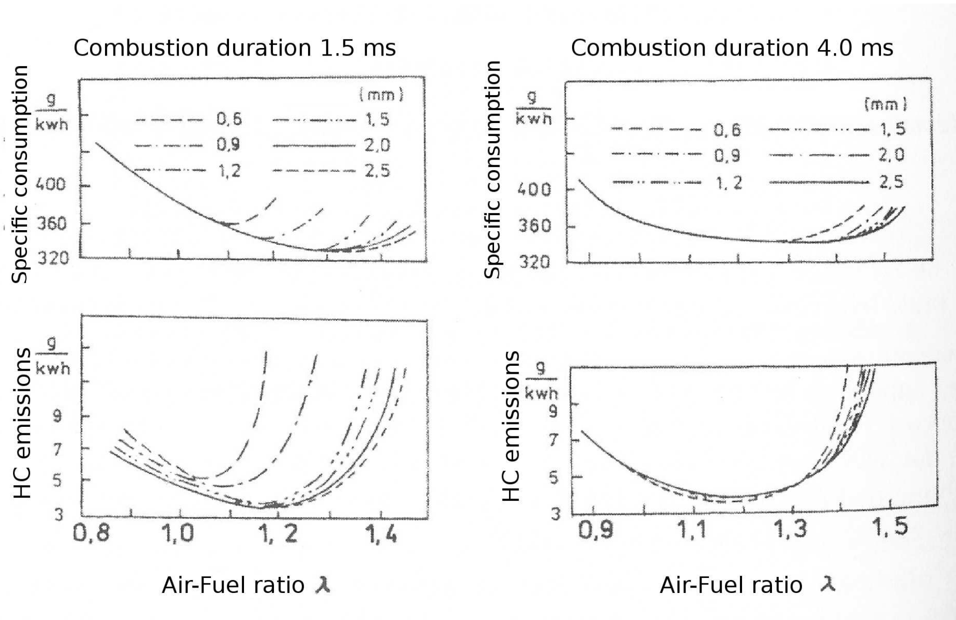


Figure 3.7: Results of the interelectrode gap and spark duration length on the specific fuel consumption and emission level of a petrol engine [7]

The reason for more efficient fuel consumption and lower hydrocarbon emissions is that a greater volume of the mixture is burnt by prolonging the spark duration and increasing the interelectrode gap, and the flame is less likely to extinguish. On the other hand, a bigger inter-electrode gap involves better isolation of the electrodes in order to prevent misfire. The spark duration depends on the charge time obtained – this is constrained by the amount of the cylinders (spark plugs) and the engine speed as well. The bigger the engine speed is and the more cylinders (spark plugs) the engine has, there is less time available for charging. The number of cylinders can be recompensed by installing a charge coil for each cylinder (spark plug). The lowest ignition voltage area can be found near the stoichiometric mixture condition, as shown in Figure 3.8 [7].

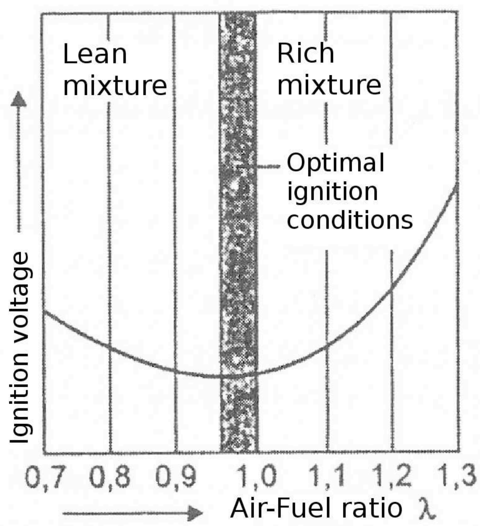


Figure 3.8: Effect of the air-fuel ratio in the ignition voltage in spark-ignition petrol engine. [7]

3.1.2.2. Qualitative power output control

Qualitative regulation is the event that the power output of an engine is controlled by regulating the fuel dose while limiting the air intake only partially or not at all. Diesel engines always operate under this concept and some indirect-injection petrol engines as well.
The condition of the air-fuel mixture changes depending upon the actual operating conditions. The mixture condition might be extremely distant from the stoichiometric point under low loads. Slight or no restrictions to the intake airflow reduce the hydraulic losses, which are in opposite, nearly inevitable using quantitative regulation.
A spark-ignition engine needs mixture stratification when it is expected to work with effective λ larger than 1.6 – this kind of lean mixture cannot be ignited.
A specifically designed injector nozzle and combustion chamber then create an ignitable mixture around the spark plug electrodes, while the rest is filled with air (cf. Figure 3.9) [8].
The engine control is more challenging using qualitative regulation, as the fuel-air mixture condition significantly affects the emissions and operation, as shown in Figure 1.10 for the petrol engine. A spark-ignition engine, while burning the rich mixture, has higher specific fuel consumption, as well as higher specific power output, cf. also Figure 3.3.
In spite of this, the hydrocarbon emissions in rich mode are higher and secondary air has to be gusted into the exhaust to oxidize the unburned hydrocarbons of the catalytic converter. Changing the operation mode to the lean area, the specific fuel consumption is getting lower, while nitrogen oxide emissions will significantly raise. Where $\lambda = 1.6$ the specific fuel consumption reaches its minimum.
Near the $\lambda = 1.6$ a pressure sensor in the combustion chamber should be applied to improve the combustion process control. At $\lambda > 1.65$, the engine cannot be operated because the mixture condition is very lean.

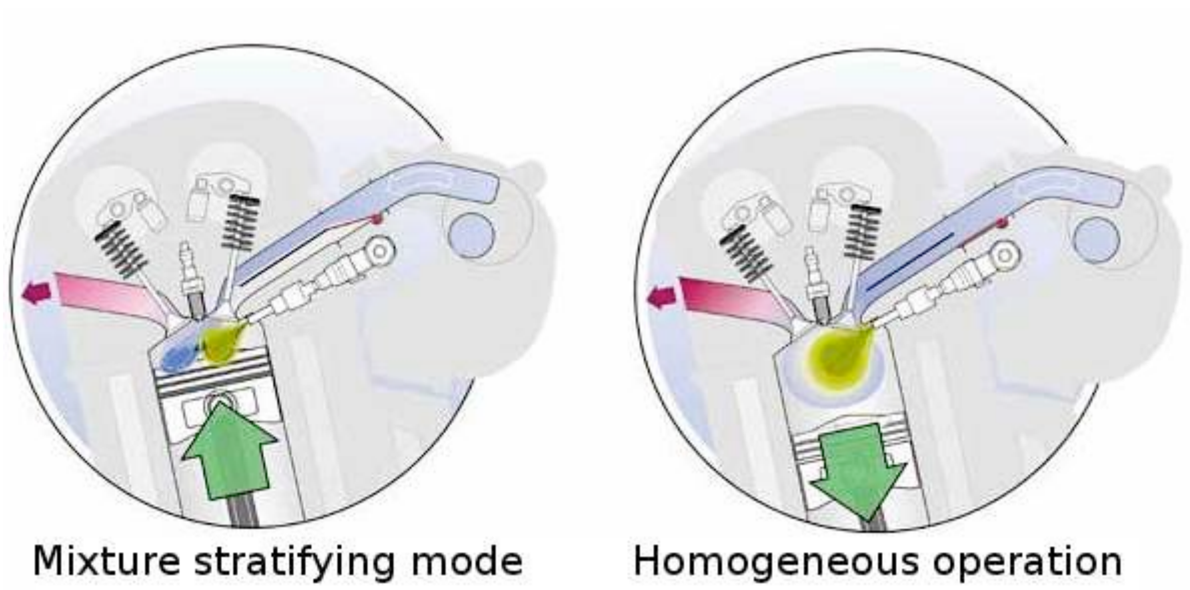


Figure 3.9: Fuel stratification in a petrol engine with very lean operation in comparison to homogeneous mixture usage. [8]

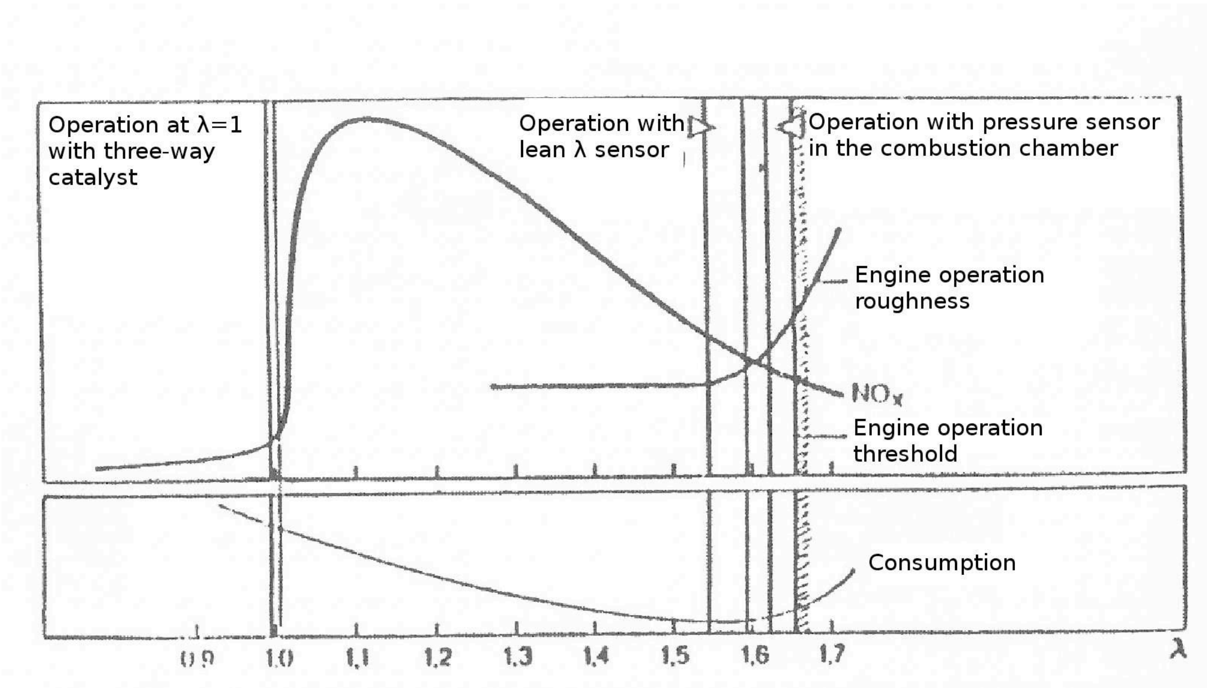


Figure 3.10: Effect of mixture composition on the emission level and operation of a qualitatively regulated petrol engine. [7]

A Diesel engine is always operated at $\lambda > 1.3$ (which is the high smoke border). In contrast to spark-ignition engines, in a Diesel engine, the fuel is ignited by injecting it into the hot compressed air in the combustion chamber, which has been heated up by swift adiabatic compression of the air.

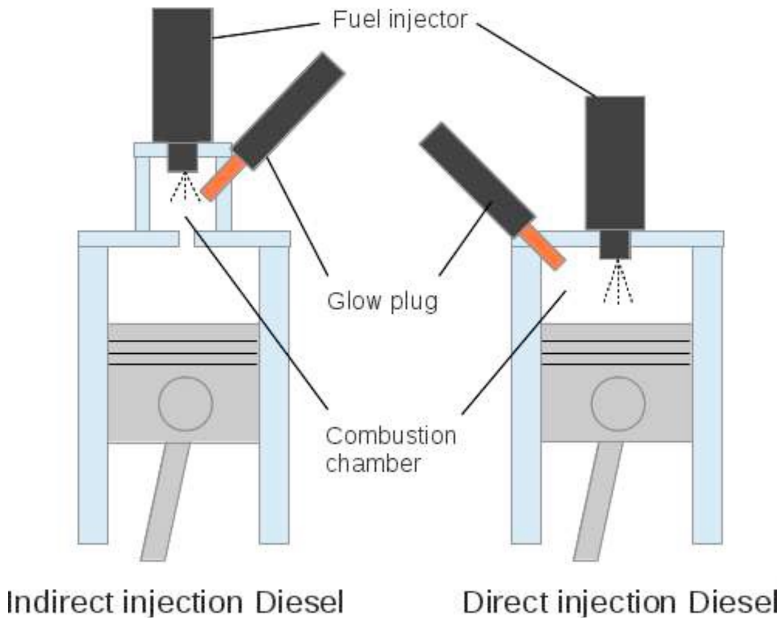


Figure 3.11. Difference between direct and indirect Diesel injection. The combustion chamber and injection system of a Diesel engine – indirect injection (left) and direct injection (right) [9].

In the direct injection, diesel engines have the advantage of lower specific fuel consumption, but it is harder to control. When injecting the fuel in a single stage, the pressure rise is very intense, which causes mechanical stress to the engine and intense noise. To reduce these negative effects, the fuel is injected in several phases, which is distributing the combustion process over a longer time duration – cf. Figure 3.12. Then the engine operation is less noisy and more comfortable.

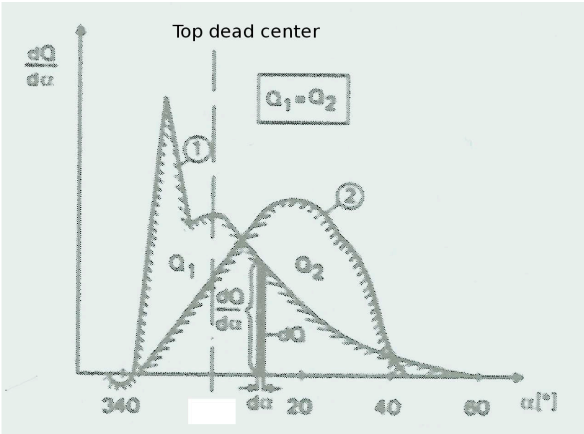


Figure 3.12: Distribution of the combustion process in a diesel engine over a longer time duration. [7, 10]

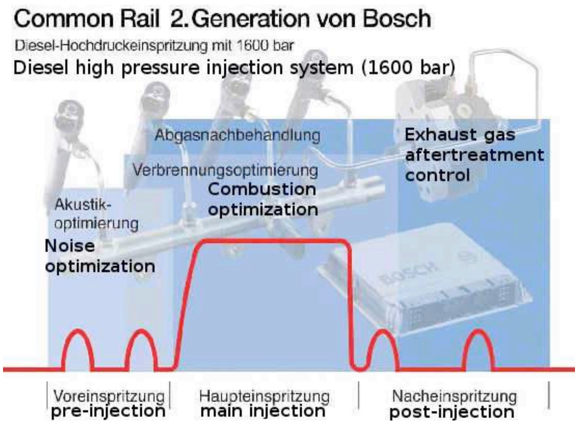


Fig. 3.13. Distribution strategy of Diesel fuel injection for the 2nd generation common-rail injection system by Robert Bosch GmbH. [7, 10]

The curve (1) in Figure 3.12 explains the heat generation using a single injection executed before the piston reaches the top dead centre. The heat is discharged quickly, causing instant pressure increase and as a result mechanical stress and noise. The curve (2) describes a phased fuel injection. In this situation, the fuel is injected in several phases where is distributing the heat expansion and pressure increase over a longer time duration, cf. Figure 3.13 and [11]. This decreases the peak pressures in the combustion chamber, reducing noise and mechanical stress.

The time duration of the injection affects engine performance and the emission level as well. Injecting the fuel earlier than in the optimal point causes effective burning of the fuel, but then it increases the NO_x emission. Injecting later than the optimal setting results in lower nitrogen oxide emissions but increases the emission of unburned hydrocarbons because the fuel does not have enough time to burn properly. cf. Figure. 3.14.

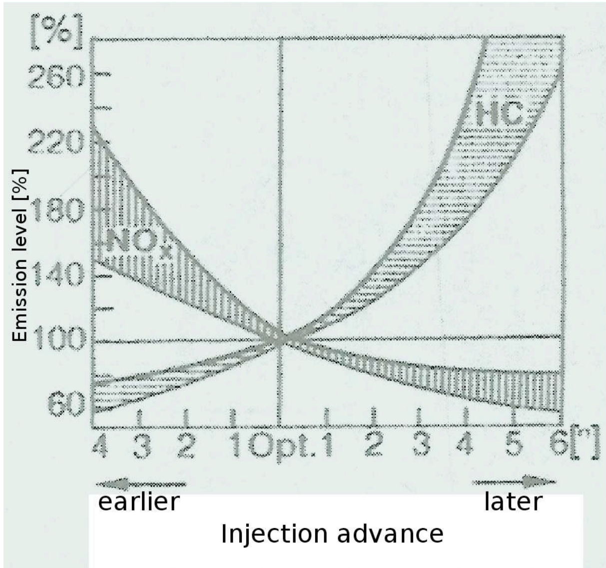


Figure 3.14: Effect of the injection timing on the emission level of a Diesel engine. [7]

Earlier injection -left from optimum (Opt.) – ensures better combustion of the fuel but increases the NO_x emissions due to a higher excess of oxygen and higher temperature. Injecting the fuel after the optimal point causes hydrocarbon emissions to increase, as the fuel does not have sufficient time to be combusted completely.

In Diesel engines, the homogeneous mixture should not be formed, because of unacceptable high pressures that would arise in the combustion chamber. Since homogeneous mixture makes potential better fuel distribution, leading to lower combustion temperatures and lower emissions levels.

3.2. Exhaust fuels after-treatment

The emission standards for petrol and diesel engines are getting tighter all the time and demanding new technical solutions. To fulfil the growing demand for specific power output, fuel consumption and emissions, the combustion engines experienced rapid development in the past two decades. Their operation has become quieter, the specific power output almost doubled thanks to the advancements in supercharging and injection technology, the exhaust fuels are cleaner because of the utilization of advanced after-treatment solutions and the fuel consumption dropped significantly.

3.2.1 Petrol engines after-treatment

Petrol engines also underwent a big improvement in the past 20 years. They do not require such complex after-treatment to achieve the recent emission limits as the Diesel engines. For the economic and simpler arrangements designed for small cars, one of the most recent technologies and commonly used is three-way catalytic converter (see Section 3.5.1.1 and cf. 12, 13), even without exhaust fuel recirculation [8]. Petrol engines designed for high power operation are modified to that purpose using state-of-the-art approaches to reach high power output while maintaining low specific fuel consumption and acceptable emission levels.
A good example of a state-of-the-art petrol engine is the recent Audi EA888gen3 1.8 TFSI (132 kW). Compared to its predecessors, quite a few innovative solutions have been implemented,

such as water-cooled exhaust manifold, a combined direct/indirect fuel injection system), variable valve lift and timing and improved thermal management.

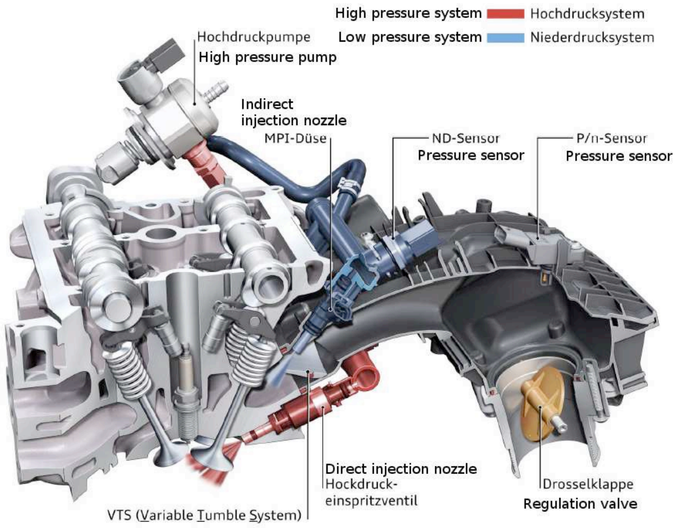


Figure 3.15: Cylinder head and intake manifold arrangement of the Audi EA888gen3 [14].

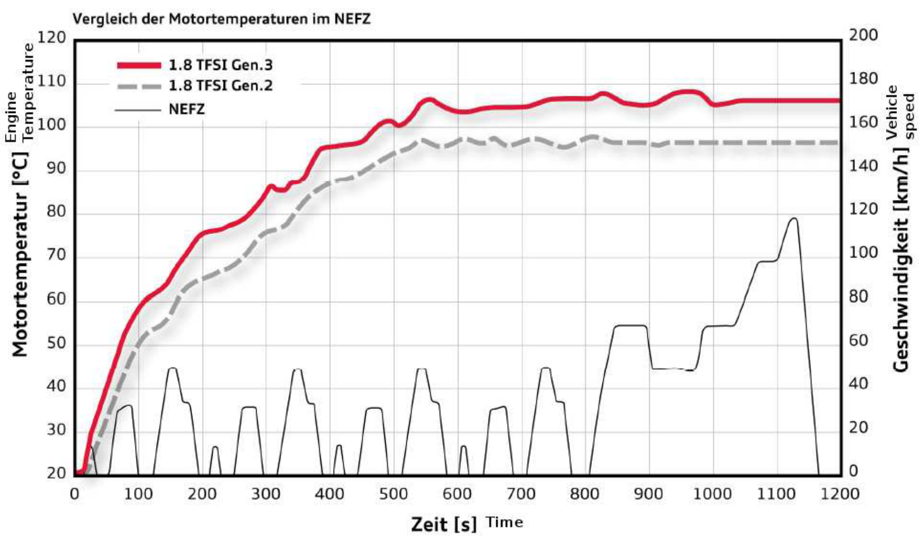


Figure 3.16: Left: Comparison of the engine operating temperature during the NEDC (former driving cycle) – previous generation (grey) vs recent (red) engine. [14]

Due to the intelligent thermal management, the Audi EA888gen3 engines reach quicker the operating temperature (cf. Figure 3.16) and the engine and coolant temperature can be rapidly adjusted to actual load conditions, minimizing the fuel consumption.

The petrol engine concept shown above enables engine down speeding (operating at very low RPM). This is advantageous for emission control (both gaseous and particulate) and high-power output while maintaining relatively low specific fuel consumption [14].

3.2.2. Diesel engines (compression-ignition engines) after– treatment

Diesel engine it is an internal combustion engine in which the ignition of the fuel, which is injected into the combustion chamber, is caused by the elevated temperature of the air in the cylinder because of the mechanical compression. Indirect injection diesel engines were commonly utilized in the early 90s (Figure 3.11). The regulation of the operation of this kind of engine is not very demanding so that they can be produced cheaply. However, the disadvantages of this type of Diesel engines is higher fuel consumption and smoke development because of the combustion chamber geometry.

Thus, direct-injection Diesel engines (Figure 3.11) are more fuel efficient, but once they were rough, loud and not very suitable for passenger cars. The first developed turbocharged direct injection engine for passenger cars was from the Italian automobile manufacturer FIAT for the FIAT Croma 2.0 TD 1988, followed one year later by Audi's five-cylinder 100 2.5 TDI. This was the world's first fully electronically controlled turbocharged direct-injection Diesel engine for passenger cars. Direct-injection engines are commonly used for heavy-duty vehicles for many years, as for these vehicles the operation roughness is not the main parameter.

For Diesel engines, a DOC (Diesel Oxidation Catalyst) was the only after-treatment mechanism operated for a long time. As the Diesel engine operates always with high temperatures and excess of oxygen, high amounts of NO_x are present in the exhaust fuels. Because of the presence of oxygen in the exhaust fuels, the elimination of the nitrogen oxides is quite challenging. Without the usage of specialized catalytic converters, the engine itself must obstruct the formation of the NO_x. This is done by the installation of the Exhaust Gas Recirculation valve (EGR, cf. Figure 3.17), by diverting a small portion of the exhaust fuels back into the intake manifold, reducing the concentration of nitrogen in the combustion mixture. This reduces also the combustion temperature which also harmful to the engine and limits the formation of NO_x throughout the combustion process.

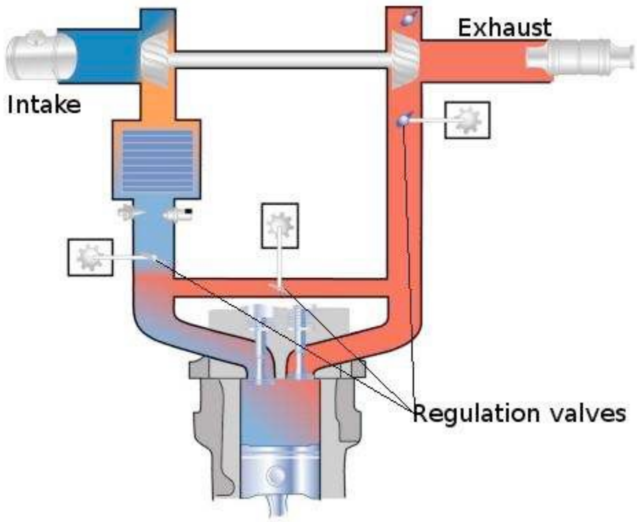


Figure 3.17: Scheme of the exhaust gases recirculation valve [8]

Usage of advanced catalytic converters is necessary; to further improve the emission properties. A Diesel oxidation catalyst oxidizes the UHCs and the NO_x need to be eliminated using dedicated systems as the NO_x Storage and Selective Catalytic Reduction or reduction converter. As the current and former Diesel engines suffer from particulate development throughout the combustion process, a filter system such as Diesel Particulate Filter (DPF, Section 3.5.2) must be installed into the exhaust fuel tract. This filter collects the formed particulates and burns them during the regeneration phases. A whole system for complete Diesel exhaust fuel after-treatment is therefore extremely complex and expensive.

3.3. Exhaust fuels after-treatment legislations. Europe legislation

The legislative implementations are an effective appliance to ensure the development of cleaner technologies in Europe. At the beginning of 1987, Europe introduced the fully central legislature system. The primary elements of the central legislature regarding living environment pollution emerged around 1965. Then, Germany with France presented a limitation of carbon monoxide and unburned hydrocarbons emissions. Soon after that, a general tendency was developed to reduce the amount of lead (Pb) in the air, as the biggest amount of lead originated from automotive fuels. The primary limits of lead content in automotive fuels announced Germany, which was 0.4 g per litter from 1972, 0.15 g per litter from 1976. Similar standards were not introduced in some other European countries. The diverse standards across Europe had a negative effect on international trade and free movement. Due to this, the European Community was required to introduce centrally regulated emission standards. During 1975, standard controlling sulphur emissions and sulphur content in the fuel was announced. After a decade later in 1985, the German minister of environment declared requirements, that from 1989 all newly manufactured vehicles need to be equipped with a catalytic converter. The implementation of a catalytic converter does not allow the driver to use lead-containing fuel, because lead is a strong catalytic poison. This caused two problems – Italian and French did not have corresponding technologies and could not sell their products on the German market anymore and German tourists traveling to these countries in the south could not refuel properly due to the unavailability of lead-free fuel. This started a debate, which resulted into the Luxembourg Compromise in 1987, introducing several standards for different vehicle classes. This was the base for all future emission standards regarding the effect of car transportation in the living environment. [15]

In the following table 3.1are summarized the Emission standards for passenger cars and light commercial vehicles. Since the Euro 2 standard, Europe legislations announce another emission limit for petrol and diesel-powered vehicles. In Diesel-powered vehicles allowed higher NO_x emissions but have more strict CO standards. Petrol-powered vehicles were excused from PM standards through to the Euro 4 stage. A particulate number standard PN (number of constituent particles in that system) has been announced in 2011 with the Euro 5b for diesel engines and in 2014 with Euro 6 for petrol engines. [16][17][18]

Table 3.1. European Emission Standards for passenger cars, g/km [19]

Stage	Date (First Registration)	CO	HC	HC+NOx	NOx	PM	PN
		g/km					Amount/km
Diesel							
Euro 1*	Januray 1993	2.72 (3.16)	0	0.97 (1.13)	0	0.97	0
Euro 2	Januray 1997	1.0	0	0.7	0	0.7	0
Euro 3	Januray 2001	0.66	0	0.56	0.5	0.56	0
Euro 4	Januray 2006	0.5	0	0.30	0.25	0.3	0
Euro 5a	Januray 2011	0.5	0	0.230	0.18	0.23	0
Euro 5b	Januray 2013	0.5	0	0.230	0.18	0.23	6 x 10 ^11
Euro 6b	September 2015	0.5	0	0.170	0.08	0.17	6 x 10 ^11
Euro 6c	September 2018	0.5	0	0.170	0.08	0.17	6 x 10 ^11
Euro 6d-Temp	September 2019	0.5	0	0.170	0.08	0.17	6 x 10 ^11
Euro 6d	January 2021	0.5	0	0.170	0.08	0.17	6 x 10 ^11
Petrol							
Euro 1*	Januray 1993	2.72 (3.16)	0	0.97 (1.13)	0	0	0
Euro 2	Januray 1997	2,20	0	0.5	0	0	0
Euro 3	Januray 2001	2,30	0.2	0	0.15	0	0
Euro 4	Januray 2006	1.0	0.1	0	0.8	0	0
Euro 5a	Januray 2011	1.0	0.1	0	0.060	0.005⁑	0
Euro 5b	Januray 2013	1.0	0.1	0	0.060	0.0045⁑	0
Euro 6b	September 2015	1.0	0.1	0	0.060	0.0045⁑	6 x 10 ^11⁂
Euro 6c	September 2018	1.0	0.1	0	0.060	0.0045⁑	6 x 10 ^11
Euro 6d-Temp	September 2019	1.0	0.1	0	0.060	0.0045⁑	6 x 10 ^11
Euro 6d	January 2021	1.0	0.1	0	0.060	0.0045⁑	6 x 10 ^11

*Values in parentheses are evidencing that exactly match the specification limits
⁑ Relates only to cars with direct injection engines
⁂ 6×10^{12}/km within first three years from Euro 6b effective dates

European emission standards were first implemented in 1993, with Euro 1 becoming the base of the law for emission standards from the vehicles. Over time the vehicles are tested under conditions defined firstly as an ECE 15 + EUDC and then the New European Driving Cycle (NEDC, see section 3.4.1) and the emission after-treatment system must work efficiently for 160 000 km.
New WLTP (World harmonized Light vehicle Testing Protocol, see Section 3.4.2) driving tests were introduced in September 2018 and will gradually replace the old NEDC tests. Therefore, to make emissions tests more reflective of real-world driving. Currently, all new vehicles are sold after WLTP testing to more closely indicate the fuel economy and emissions when the car is actually driving and include an additional real-world driving emissions (RDE) test to measure the regulated pollutant emissions. The RDE complements the WLTP testing and is used on-road conditions instead of the lab and operates with a portable emissions measurement system to record the emissions. The RDE indeed enforces intermediate steps towards a truly new emission standard, Euro 7, which is likely to come into power in the mid-2020s.

All newly produced automobiles are Euro 6 standard and are split into a number of different requirements, the letters following the number 6 (b, c or d) are expressing the fact that they satisfy with the up-to-date type of the emission standard. Euro 6 standard has been updated from the year 2014 and it will continue to be updated during the following years. Furthermore, because of the Dieselgate scandal (more exactly the fact that independent tests revealed extreme differences between NO_x emissions measured in the lab conditions and real-life measurements), the EU is calling these updates Euro 6c, Euro 6d-Temp and Euro 6d instead of keep on counting and name them with Euro 7, 8 and 9. This is the reason why Europe changed the name of the standard from Euro 6b to Euro 6c, which means for Euro 6c that NO_x is limited respectively to

60 and 80 mg/km for petrol and diesel-powered vehicles and is the standard for WLTP measurements. [19]
However, Euro 6d-TEMP is the one for RDE (additional on-road measurement to guarantee compliance with the new Euro 6d-TEMP emissions standard, see section 4.3). It is a temporary measure, which petrol-powered vehicles can emit 126 mg/km while tested on the road, diesel-powered vehicles 168 mg/km and the "road emissions value", including a measuring tolerance, must not go above 2.1 times the laboratory limit for NO_x. By 2020/1, when Euro 6d takes effect, the allowed deviation between RDE and WLTP will be reduced to some percentage. Petrol-powered vehicles must then stay below 90 mg/km, diesel-powered vehicles are to keep their NO_x emissions under 120 mg/km - precisely, the standard has not changed, but the measuring method has. [19]

Suggestions are that Euro 7 potentially will come into around 2025, by when it is possible that a number of European cities will have a switch to Ultra Low Emission Zones and/or diesel bans.

3.4. Driving cycles and Emission measurement

To assure a mutual comparison of consumption and emission levels for all carmakers, various techniques have been developed for obtaining important data. These techniques vary for different regions, which were built to simulate real driving conditions.
The most broadly used cycles are the American FTP/SFTP, the former European NEDC, and the current European WLTP cycle [6]. These driving cycles consist of several measures simulating city driving, highway driving, and aggressive driving.

The riding cycle also classifies similarly parameters, which all cars need to fulfil, including the start temperature, for the manually shifted vehicles – the gear change points, the payload and the start of measurements. During the measurement, the car is installed onto a test bench [17] (Figure 3.18). Once the test is performed, a skilled operator drives the vehicle to suit the cycle definition of acceleration, deceleration, gear shifting, and speed. Throughout the test procedure, the exhaust fuels are accumulated and then analysed. From the carmaker's point of view, the defined driving cycles are used as a standard for car efficiency and are necessary for vehicle diagnostics.

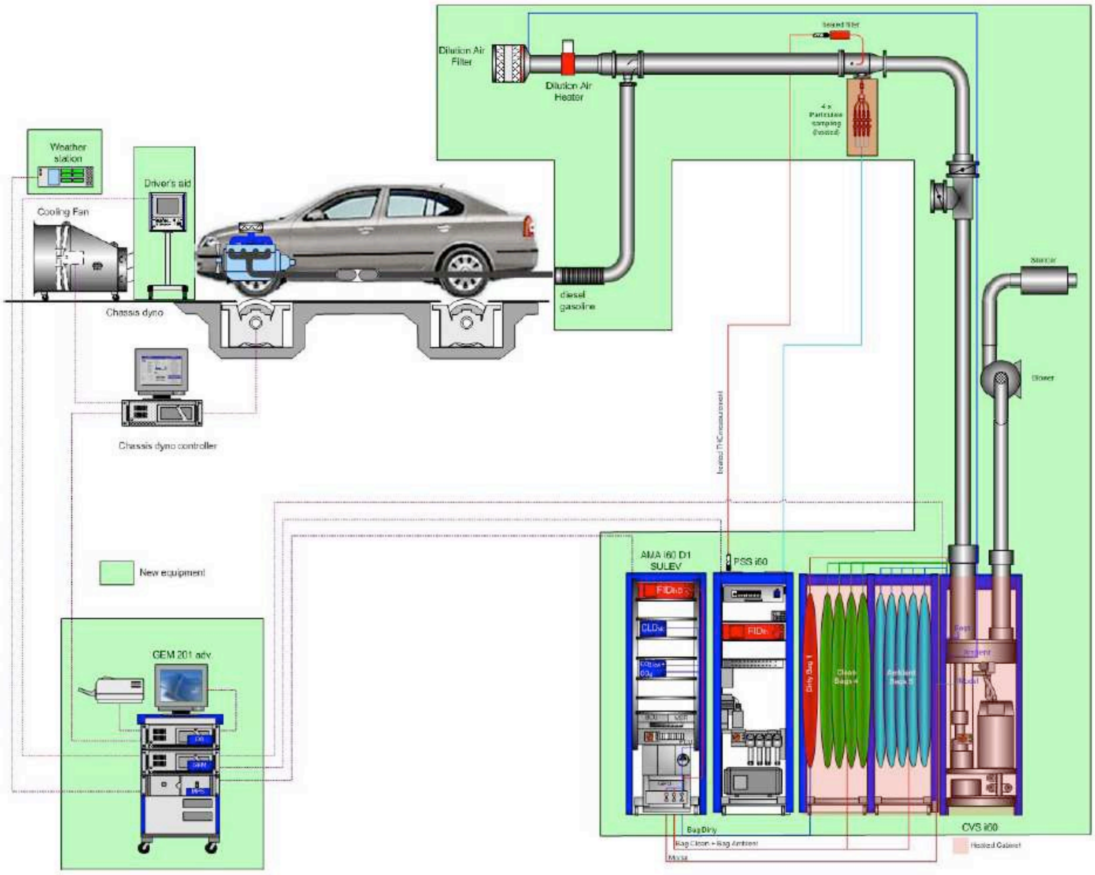


Figure 3.18: Test bench for examining the automobile's emissions and fuel consumption. [20]

What is measured is the emission and fuel consumption as well as the electrical range in the case of hybrid and electric vehicles. If the results meet the limits required by the EU under the so-called Euro-X standards, the competent national authority shall issue the so-called regional territory type approval, in this case, the EU. This implies that this precise model can be sold and used on the roads in that territory once type approved. Correspondingly, the type-approval with certified technical consumption figures is used in many EU countries to calculate, for instance, the tax of the motor vehicles or is used as the basis for the environmental sticker assignment. The EU Commission also calculates the average EU fleet CO_2 emissions value based on total market sales of the car models. This value should be below 95 g/km to achieve the EU's climate protection targets from 2020. Furthermore, the emission values and consumption from the driving test cycle must also be published in publicity and communications activities, such as brochures, blogs or showrooms. All producers are required to report the outcomes – so-called "labelling". [21]

3.4.1 New European Driving Cycle

Effectively from 2000 (Euro 3) until September 2018 the vehicles have been tested under conditions defined by the New European Driving Cycle (NEDC). The formerly used NEDC is used to determine the behaviour of the vehicle over a broad range of driving conditions regarding emissions and fuel consumption.
The NEDC is a three-part synthetic driving cycle representing urban driving conditions (ECE-15) and extra-urban driving conditions outside (EUDC). The car must be conditioned to 25°C before the test.

The test bench is designed with parameters matching to the automobile class (mass and driving resistances, such as tire roll resistance and aerodynamic drag resistance). Table 3.2 and Figure 3.19 summarize the NEDC velocity profile. [20]

Table 3.2: Velocity evolution during the New European Driving cycle. [5]

Characteristics	Unit	ECE-15	EUDC	NEDC
Distance	km	4×1.013=4.052	6.955	11.007
Duration	s	4×195=780	400	1180
Average Speed	km/h	18.7 (with idling)	62.6	33.6
Maximum Speed	km/h	50	120	120

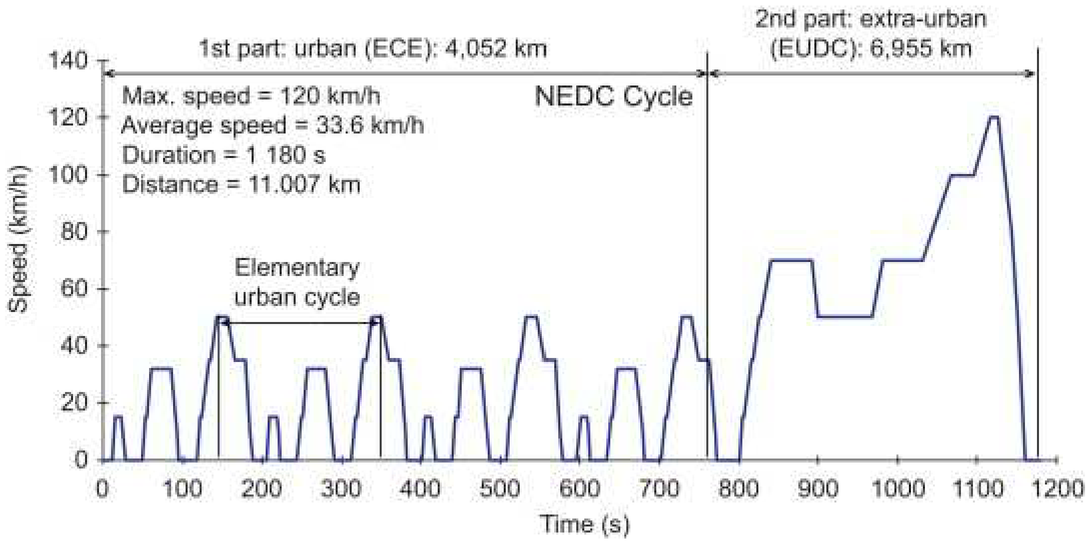


Figure 3.19: Velocity evolution during NEDC [20]

The cycle can be easily simulated, however various driving resistances on fuel consumption can be derived [8] (see Table 3.2).

Resistance		Extra consumption (l/100 km)	
		Gasoline	Diesel
Vehicle mass[a]	100 kg	0.15	0.12
Aerodynamic drag [b]	0.1 m^2	0.14	0.11
Tire roll resistance[c]	0.1 %	0.08	0.06
Electric current[d]	1 A	0.014	0.011
mechanical resistance[e]	1 kW	0.66	0.53
wheel roll resistance[f]	1 Nm	0.020	0.016
Tractive effort[g]	1 N	0.0062	0.0049

Table 3.3: *Influence of various resistances on fuel consumption during NEDC.* [8]

a) Engine and gear ratios unchanged, the mass difference influences the driving performance
b) Valid for NEDC ($v = 33.6km/h$). At constant 130 km/h quadruple influence, at constant 180 km/h octuple influence

c) Valid for 1300 kg-vehicle; the influence is proportional to weight differences
d) Valid for $U = 14V$
e) Effort necessary to compensate mechanical resistance of the power- and drivetrain. For example: 1 kW mechanical resistance corresponds during the NEDC to a tractive effort of 107 N (or 6 Nm at the crankshaft at $n = 1600/min$) over the NEDC
f) Wheel torque caused for example by residual braking moment and wheel bearing friction
g) Valid for constantly effective driving resistance of 1 N

3.4.2 The Worldwide harmonized Light vehicles Test Procedure

Coming into force in 2017, the new World Harmonized Light Vehicle Testing Protocol (WLTP) test was launched formally in September 2018 to replace the former NEDC cycle test, in order to get emission measurements more reflective of real-world driving. WLTP is a novel emission test method for the determination of emission characteristics and fuel consumption from light-duty vehicles. The tests have been established by the UN ECE GRPE (Working Party on Pollution and Energy) group. It was originally designed as a worldwide harmonized test procedure. For this purpose, the cycle was effectively created by sample driving models "from all over the globe." However, the goal of worldwide harmonization could not be achieved, as the US and China withdrew from the talks on how consumption is measured, while other countries objected to the "WLTP" design. The WLTP is currently being applied in the EU and is being implemented in other countries such as Japan and India.

The WLTP methods include some WLTC test cycle runs for various power-to-mass (PMR) car classifications. Three classes of the WLTC test procedure exist, which are applied to vehicle categories defined by the power-to-mass ratio (see Table 3.4), where the mass corresponds to the curb weight of the vehicle (as defined by ECE-R83, see [23]). The WLTP definition is also dependent on the vehicle maximum velocity (v_max), which the manufacturer declared for the approved vehicle type according to ECE-R68 (see [24]) without using any restrictions or safety-based limitations [5]. The curb mass is the "unladen mass" as described in ECE R83 [3903], which the driver is not included. Nevertheless, EU legislation [3635] appear inconsistent with GTR 15 and replace the curb mass with “mass in running order”, which includes the driver and is 75 kg higher.

Fig. 3.20. WLPT Vehicle Test Procedure [Skoda Auto Employee Portal]

Cycle adjustments are acceptable to accommodate drivability problems for cars with power to a mass ratio near the borderlines or with maximum velocity limited to values below the maximum velocity needed by the cycle.

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 3.4. WLTC test cycles [25]

The Class 3 represents vehicles driven in Europe and Japan and it the class with the highest power-to-mass ratio. Class 3 vehicles are split into 2 subclasses according to their maximum velocity: Class 3a with v_{max} < 120 km/h and Class 3b with $v_{max} \geq$ 120 km/h. The selected parameters of the above-mentioned vehicles are listed in Table 4.2, the vehicle acceleration and speed evolution for Class 3b is represented in Figure 1.20. (in this representation, Class 3a dash would look very alike).

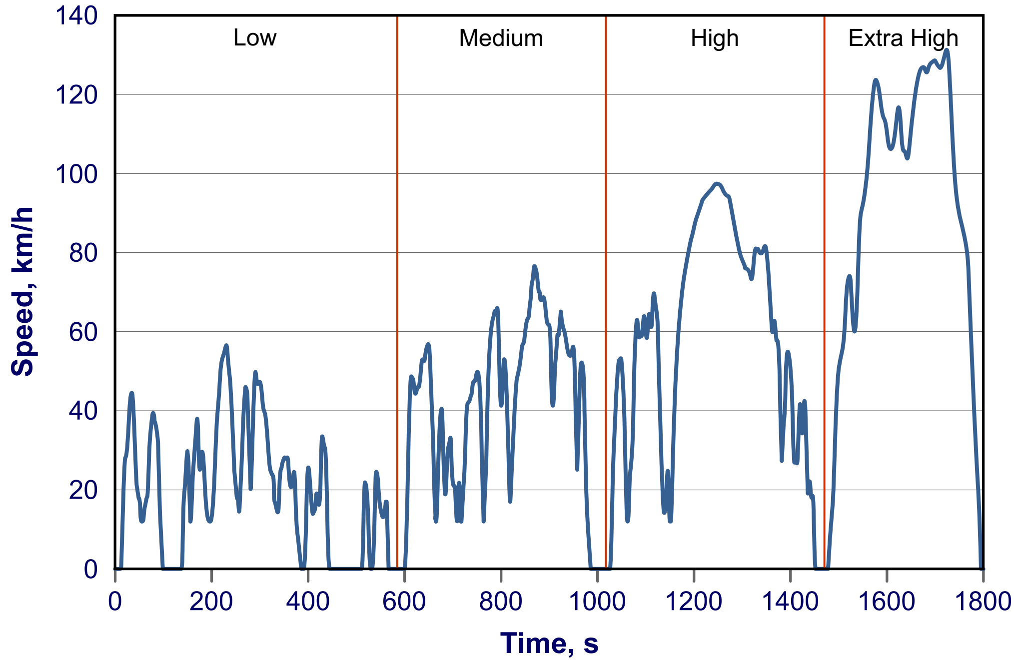


Figure 3.20. WLTC cycle for Class 3b vehicles [25]

The Class 2 WLTC test cycle represents low-powered vehicles driven in Europe and Japan and vehicles driven in India. Selected parameters of this class of vehicles are shown in Table 3.6, the speed and acceleration evolution are shown in Figure 3.22.

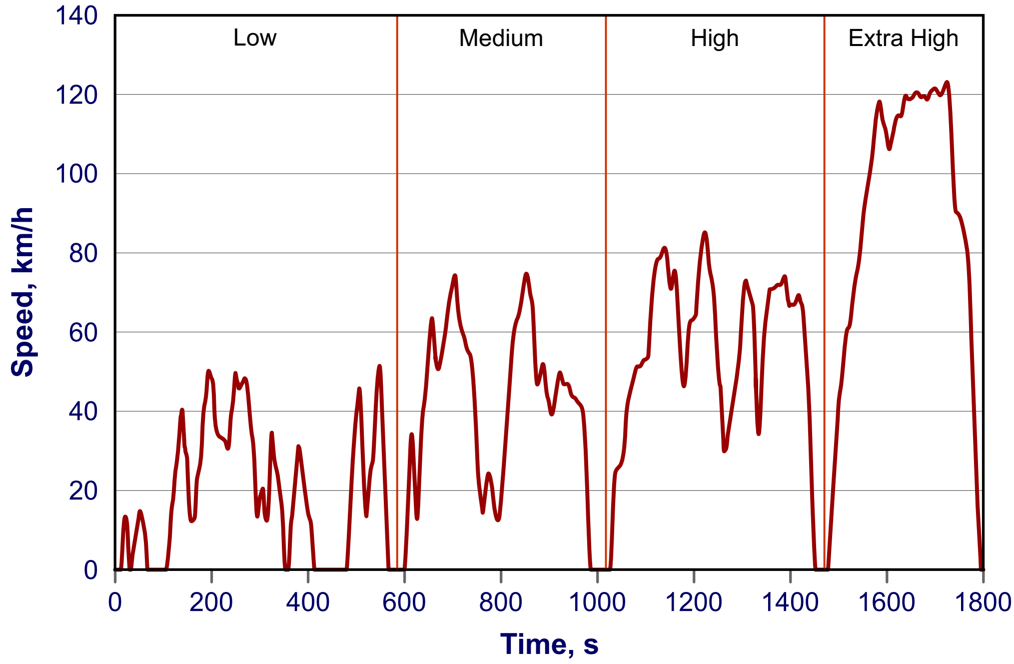


Figure 3.22 WLTC cycle for Class 2 vehicles [25]

The vehicles with the lowest power-to-mass ratio are subject to the Class 1 WLTC test cycle procedure. Selected parameters of this class of vehicles are shown in Table 3.7, the speed and acceleration evolution are shown in Figure 3.23.

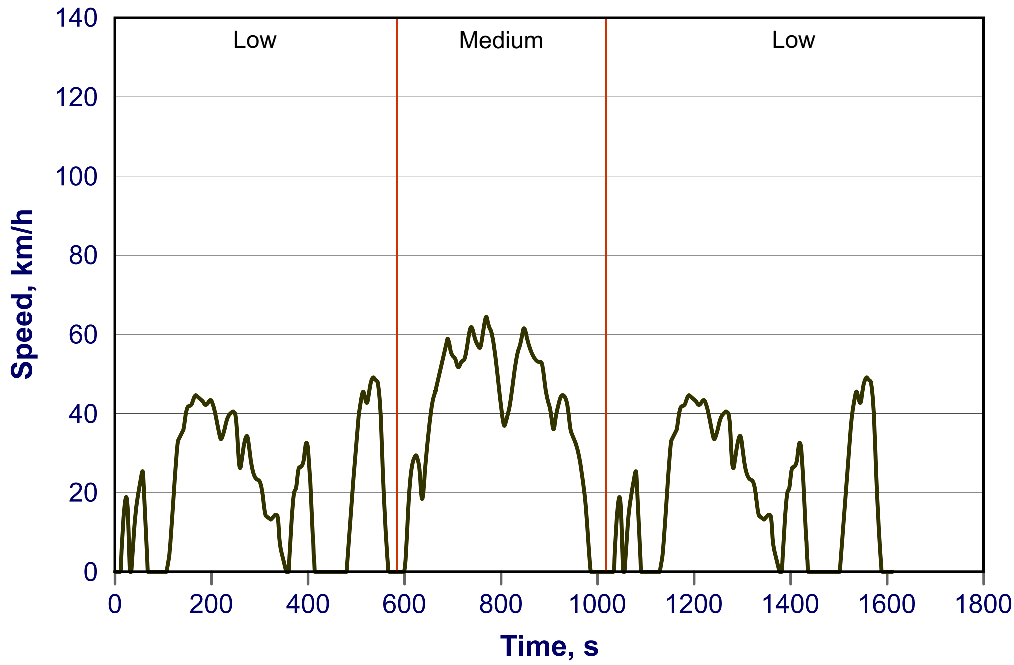


Figure 3.23 WLTC cycle for Class 1 vehicles [25]

Table 3.5. Selected parameters of the WLTP Class 3 cycle [25]

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 3.6. Selected parameters of the WLTP Class 2 cycle [25]

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 3.7. Selected parameters of the WLTP Class 1 cycle [25]

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**						

3.4.2.1 Tests for Hybrid & Electric Vehicles

Special requirements for testing multiple types of hybrid-electric and electric vehicles are included in the WLTP, such as OVC-HEVs (off-vehicle charging hybrid electric vehicles); NOVC-HEV (not off-vehicle charging hybrid electric vehicles); and PEV (pure electric cars).\

Class 3 cars are categorized as all OVC-HEVs, NOVC-HEVs, and PEVs. Emissions and a range of other parameters are evaluated in both charge-depleting and charge-sustaining models over the corresponding Class 3 (Class 3a or Class 3b) cycle. Furthermore, certain parameters are evaluated over WLTC city-cycles, consisting only of stages of low and medium velocity. Table 3.8 summarizes the test matrix.

Table 3.8. WLTC test matrix for hybrid and electric vehicles [25]

		WLTP		WLTP city
		Charge-depleting	**Charge-sustaining**	**Charge-depleting**
		Criteria Emissions, FC, CO_2, AER, EAER, R_{CDC}, R_{CDA}, E_{AC}	*Criteria Emissions, FC, CO_2*	*AER city, E_{AC} city*
OVC-HEV	Class 3a	Low 3 + Medium 3-1 + High 3-1 + Extra High 3	Low 3 + Medium 3-1 + High 3-1 + Extra High 3	Low 3 + Medium 3-1
	Class 3b	Low 3 + Medium 3-2 + High 3-2 + Extra High 3	Low 3 + Medium 3-2 + High 3-2 + Extra High 3	Low 3 + Medium 3-2
NOVC-HEV	Class 3a	--	Low 3 + Medium 3-1 + High 3-1 + Extra High 3	--
	Class 3b	--	Low 3 + Medium 3-2 + High 3-2 + Extra High 3	--
PEV	Class 3a	Low 3 + Medium 3-1 + High 3-1 + Extra High 3	--	Low 3 + Medium 3-1
	Class 3b	Low 3 + Medium 3-2 + High 3-2 + Extra High 3	--	Low 3 + Medium 3-2
Abbreviations: AER - All-electric range EAER - Equivalent all-electric range EAC - Recharged energy FC - Fuel consumption NOVC-HEV - not off-vehicle charging hybrid electric vehicle OVC-HEV - off-vehicle charging hybrid electric vehicle PEV - pure electric vehicle RCDA - Charge-depleting actual range RCDC - Charge-depleting cycle range				

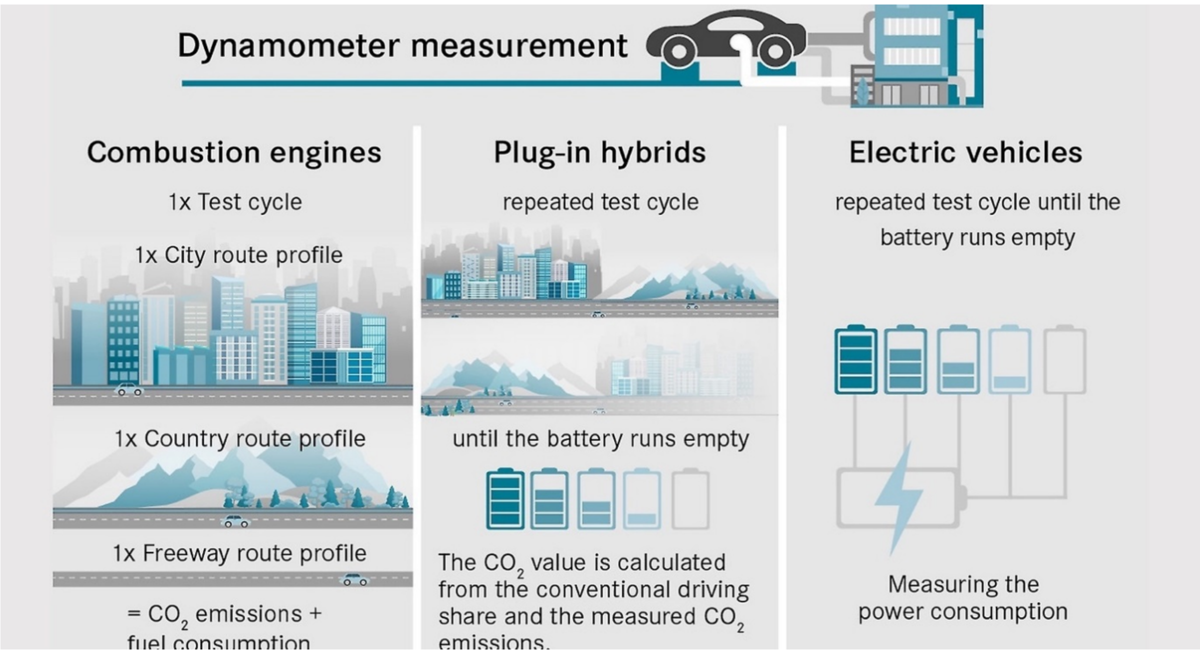


Figure 3.24. Dynamometer measurements for Combustion engines, Plug-in hybrids and Electric Vehicles [26]

3.4.2.2 WLTP and NEDC - Comparing the measurements

Although the NEDC may be out-dated, it is still an important measurement. This means that all car models will now be checked under the WLTP test procedure to be newly licensed for emissions. At the same time, however, an NEDC consumption value for these vehicles will continue to be calculated and will continue to be shown in sales materials and all other publications as the legally required figure in the near future.
Furthermore, compliance with the so-called CO_2 fleet (the average value of the fleet of each vehicle manufacturer), which serves to meet the climate goals, will still be shown in the NEDC up to and including 2020. Consequently, "NEDC values" will proceed to be calculated from the WLTP measurement in this transition period. This is performed using the so-called " CO_2MPAS (CO_2 Model for Passenger and commercial vehicles Simulation) tool," which is made accessible to convert WLTP values to NEDC values by the legal officials. Despite all the modifications, the test's fundamental concepts stay unchanged depending on the type of powertrain. Here are the measurement's primary characteristics:

Vehicles with internal combustion engine	Plug-in hybrid vehicles	Electric vehicles
A dynamometer cycle, defined by duration, route profile (city, country, and freeway), temperature conditions, acceleration, etc., is run once.	The cycle is repeated, similarly to vehicles with a combustion engine, until the battery of the hybrid vehicle is fully discharged. This measures the all-electric range.	The cycle is repeated, similarly to a plug-in hybrid, until the battery is fully discharged.

As the result, the fuel consumption is calculated from the CO_2 emissions. The pollutant emissions (NO_x, particulates, …) are also measured.	The electric range as a ratio of the total range yields the utility factor (UF). The *PiH* utility factor is between 100% (all-electric vehicle) and 0% (combustion engine only).	A charger equipped with an electricity meter is used to measure the power consumption in kWh until the battery is fully charged.
	The CO_2 value is calculated from the conventional driving share and the measured CO_2 emissions.	The electricity consumed and the range of the vehicle yield the electricity demand in kWh/100 km.

Table 4.6. Main features of the measurement at a glance [26]

As with the former NEDC, measurement is performed on a dynamometer and for all automobile's producers is required standardized, reproducible and similar test conditions. On the other hand, the pioneer WLTP cycle delivers test outcomes that are closer to actual driving conditions and thus provide higher clarity. However, it also remains clear that a standardized test cycle cannot represent each individual's particular consumption and that deviations will proceed to occur.
What is the new cycle going to do?
Measurement processes also have to progress over time. Over the previous 20 years, vehicles and customer conduct have experienced significant modifications. For instance, our cars have more powerful engines and more optional gear that impacts the consumption; also, on average, daily driving distances have become longer, while travel times have risen because of the traffic congestion. The WLTP is designed to take more accurate outputs of all these factors. The primary modifications are the following:

Parameter	WLTP	NEDC
Starting temperature	cold	cold
Cycle time	1,800 s	1,180 s
Endurance	242 s	267 s
Stop share	13.4 %	22.6 %
Distance	23,262	10,931
Maximum speed	131.3 km/h	120 km/h
Average velocity	46.5 km/h	33.35 km/h
Temperature	23 °C	25+/-5 °C
Special equipment of the individual model	are considered for weight, aerodynamics, rolling resistance, on-board power requirements; without air conditioning during phase I.	out of tyres are disregarded; without air conditioning

Table 3.9. Main changes between WLTP and NEDC measurements [21]

The advantages of the new test cycle:
• WLTP offers a more realistic measure for clients to compare the usage and emissions of different car types.
• It also offers a legally credible basis for certifying new cars for the auto producers.
• As required by the new Euro 6d TEMP standard, in addition to consumption and emission measurements on the dynamometer, it will also be necessary to meet emission limits on the road in the future. This resulted in the RDE (Real Driving Emissions) test being developed, which was also launched on September 1, 2017. This includes using a portable emission measurement system (PEMS) to measure vehicle emissions in real road traffic.
All of this will lead to a much more realistic depiction of the consumption and emissions of the new vehicles. However, according to the German Automotive Industry Association (VDA), it is predicted that, on average across the EU (weighted by unit sales), the change from NEDC to WLTP will imply a 22% rise in CO_2 scores compared to NEDC-certified automobiles. This has the drawback of the same vehicle having apparently worse emission data, although there has been no change in technology only the emission measuring method is showing more accurate and realistic data. [26]

3.4.3 Real-world driving emissions (RDE) - Measurement of emissions in real road traffic.

When it comes to emission measurement, it matters is what happens on the road eventually. That's why the so-called RDE test supplements the WLTP laboratory measurement. For the driving test, the vehicles are fitted with a so-called PEMS (Portable Emission Measurement System) for portable emission measurement. The real measurement is carried out by a Technical Services (TÜV in Germany or similar). However, in the future, it is scheduled that field measurements may also be carried out by certified third parties allowed to formally report the outcomes as a field test for the type-approval authority.

The limits are legally prescribed by the Euro 6d TEMP norm. At first look, nitrogen oxide (NOx) emission limits of 80 mg/km for diesel and 60 mg/km for petrol-powered vehicles do not alter compared to Euro 6a, b, c. Furthermore, Euro 6d TEMP is requiring an additional measurement of the RDE on the highway. This will occur in two stages.
• In the first stage, which started on 1 September 2017, a vehicle must show on the road that it does not emit more than 2,1 times the legal NO_x limit for the laboratory test or 1,0 times the particulate emission (PN), there is a measuring tolerance of 0,5.
• As of 2020/2021, the "on-road" value of nitrogen oxides (NO_x) must no longer exceed the laboratory limit–a maximum measuring tolerance of 0.5 of the laboratory limits will still be available, but the EU Commission will review this tolerance annually with a view to lowering it. [26]

The measurement concerns nitrogen oxide (NO_x) and particulate emissions (PN), as well as carbon monoxide (CO), which is subject to mandatory monitoring. Driving and measuring takes place in actual daily traffic. Continuously in accordance with the regulations of the road traffic. However, the road must fulfil established overall circumstances which ensure that the test drive involves statistically appropriate driving manoeuvres as well as road/weather conditions.

Vehicles that that are covered by the RDE are newly certified vehicle models in the first stage since first of September 2017. In addition, as well as, all the new vehicle models that are already on the market from first of September 2019.

With respect to all relevant dates for the new norms, a difference is made with respect to the scope of implementation between the "New Types" and the complete manufacturer’s portfolio of new vehicles, which is defined as "All Types":
• New Type (NT): a new product project or a facelift, i.e. a first-time certified car.
• All Types (AT): a current model series already being manufactured and still being sold as new vehicles. Therefore, this does not include already used vehicles. NT are therefore a subset of AT. [26]

RDE will lead in considerably more realistic consumption and emission values in conjunction with the new WLTP test cycle. But what's particularly relevant from the customer's point of view is that even the RDE emission figures won't reflect average real driving, because that's something that just doesn't exist and hard to measure. Both the road profile and driving style and as well as the payload are individual parameters that make it difficult for each driver to have a representative, average value.

Figure 3.25. Emission are being measured with emission portable measurement system [Skoda Auto Employee Portal]

3.5. Current Control Technology from the combustion engines in EU

Catalysts and filters are component of a complete system where all components have to work together to obtain maximum emission reduction. The fuel and fuel system, the engine and its combustion system, sensors and location of the filter and the catalyst combine with the electronic control system operate together to deliver maximum reduction of the emissions.

3.5.1 Catalytic converters in automobiles

To ensure low emission level and high engine performance, various components have been added to the powertrain, increasing its overall complexity. The most important elements are the system of partial exhaust gas recirculation, probes measuring the exhaust gas composition, electronic control units and monolith catalytic converters, which represent the core of the entire system. Such a monolith converter is made from base structure (mostly cordierite or metal), on which a porous layer (typically Aluminium Oxides or zeolites) is applied. The porous layer contains catalytically active metal crystallites (Platinum, Palladium, and Rhodium) and substances capable of adsorbing some gaseous components (cerium oxides for oxygen adsorption, barium oxides for storage of nitrogen oxides). For their excellent performance and high efficiency, especially after massive expansion of direct injection and supercharging in passenger cars during the last 20 years, the Diesel engine still gains popularity. Nevertheless, the Diesel engine is a little bit complex regarding the chemical purity of its operation. In Diesel engines, more particular substances and nitrogen oxides are formed. To counter particulate matter emissions, special monolith filters (DPF) are used. As the Diesel engine always runs under lean conditions, it is not possible to eliminate the nitrogen oxides in a similar simple way as in stoichiometric gasoline engines and dedicated converters capable of adsorbing the nitrogen oxides must be utilized.

An automotive catalytic converter must satisfy many requirements. It must work under low and high temperatures, be tolerant to catalytic poisons like sulphur [27] and resist to mechanical stress (thermal expansion, vibration from engine and road, gas flow pulsations). The first experimental converters were based on compounds of nickel and copper. These were unfortunately extremely sensitive to catalytic poisons and did not have sufficient thermal resistance [28]. Experiments with ruthenium and iridium compounds were also conducted, but the oxides of these metals are not very stable and thus it was not possible to effectively manufacture a catalytic converter, which would not decompose at higher temperatures [29]. Experiments [30] soon showed, that the catalytic converters containing rhodium are under some conditions capable of reduction of nitrogen oxides. From these catalysts later three-way converters (TWC) have been developed (see section 3.5.1.1).

The emissions of a Diesel engine contain in all modes of operation relatively large amount of oxygen. Under these conditions, the reduction of nitrogen oxides is not possible; only unburned hydrocarbons and carbon monoxide can be oxidized [31]. Next issue is the low temperature of the exhaust gases and the presence of sulphur in the exhaust gases (although nowadays nearly sulphur-free fuel is being used in Europe). The conditions in the exhaust tract of a Diesel engine forced the development of special catalytic converters capable of storing nitrogen oxides. This type of catalytic converter is being called a Lean NO_x Trap (LNT) or nitrogen oxide storage and reduction converter (NSRC). The conditions necessary for reduction of the stored nitrogen oxides are realized by temporarily switching the engine operation mode to rich mode, where excessive fuel is injected and during this phase, due to presence of an excessive amount of reducing agents in the gases, the stored nitrogen oxides are decomposed ideally to nitrogen and water [31, 32]. Another possibility is to introduce a reducing agent separately into the exhaust tract, which also helps to remove nitrogen oxides from the exhaust gases in a way called selective catalytic reduction (SCR) as mentioned in the section 3.5.1.3.

3.5.1.1 Three-Way Catalysts (TWC)

The TWC is designed by substrate containing platinum, palladium and rhodium (catalytic metals) and cerium & zirconium oxides (for storing oxygen and to ensure mechanical stability at high temperatures). The TWC is used in cars equipped with spark-ignition engines running on stoichiometric air-fuel mixture. They are more thermally resistant catalysts with enhanced stability at high temperatures, which make it possible to mount the catalytic converter nearer to the motor and to boost the life of the catalyst, especially during intense driving circumstances. It is necessary to use precious metal catalysts with stabilized crystallites and washcoat materials which maintain high surface area at temperatures around 1000°C. Improved oxygen storage elements stabilize the washcoat's surface area, maximize the air/fuel for three-way operation and indicate the catalyst's' condition for on-board diagnostics systems (OBD).

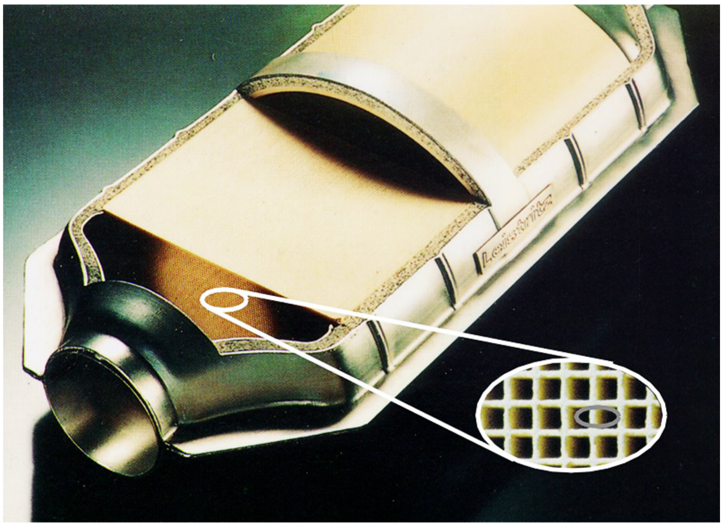


Figure.3.26. Three-way catalytic converter [13]

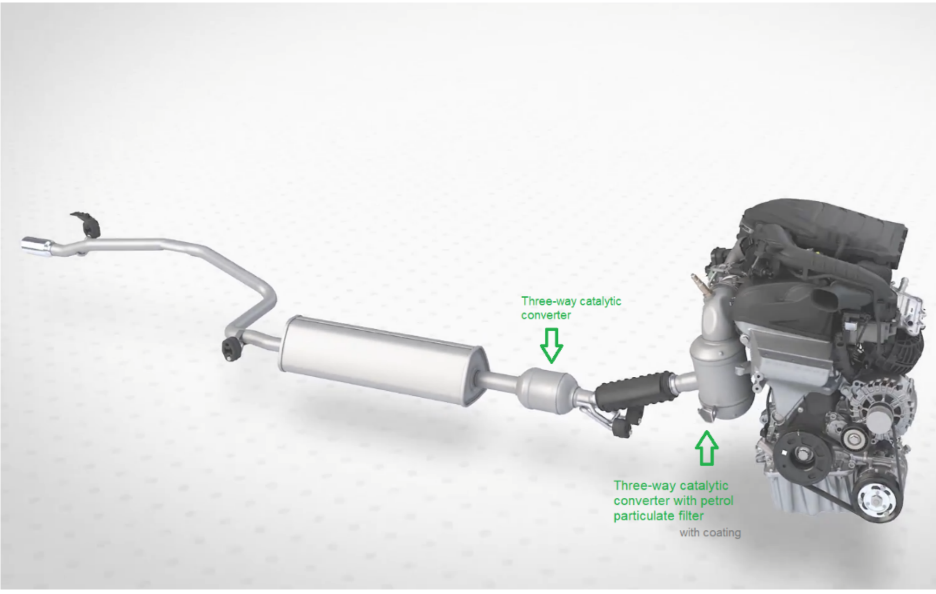


Figure. 3.27. Three-way catalytic converters, one close to the engine with petrol particulate filter for faster light-off, with underfloor catalyst and oxygen sensor in the recent model Škoda Scala. [Skoda Auto Employee Portal]

The three-way catalyst is used to reduce emissions of the three main pollutants (CO, HC and NOx), simultaneously operating around stoichiometric air-fuel ratio (λ=1). Under these conditions CO, unburned HC and H_2, which are present in the exhaust fuels and reacts as very active reducing agent, can reduce the NOx. The main product of the NOx reduction above the light-off temperature under stoichiometric conditions is nitrogen (cf. reactions 3.1–3.2) [33].

$$CO + NO \rightarrow CO2 + \frac{1}{2}N_2 \tag{3.1}$$

$$C_xH_y + 2(x + \frac{y}{4})\,NO \rightarrow x\,CO_2 + \frac{y}{2}H_2O + (x + \frac{y}{4})\,N_2 \tag{3.2}$$

$$H_2 + NO \rightarrow H_2O + \frac{1}{2}N_2 \tag{3.3}$$

During the cold start N_2O is the main nitrogen-containing product on platinum and rhodium-based catalysts, including the TWC, (see Eq. 3.4). Depending on the conditions of the composition of the catalyst and the stream, the formed N_2O may eventually react further with the reducing agents (CO, H_2) forming N_2 at high temperatures (see Eq. 3.5) [34][35].

$$CO + 2\,NO \rightarrow CO_2 + N_2O \tag{3.4}$$

$$CO + N_2O \rightarrow CO_2 + N_2 \tag{3.5}$$

High conversions of all three pollutants can be reached only under stoichiometric conditions. Conversion of CO and HC is not adequate under rich conditions and eventually NH_3 is created as a by-product of NOx reduction (see Eq. 3.6 and Eq. 3.7). Under lean conditions (excess of oxygen, which is typical for Diesel-powered vehicles — see section 3.5.1.2), the reducing agents reacts preferentially with O_2 and the NOx stay unreduced or are only partly lowered to N_2O (see figure 3.28), meaning that TWC only works as an oxidation catalyst..

$$5\,H_2 + 2\,NO \rightarrow 2\,H_2O + 2\,NH_3 \tag{3.6}$$

$$5\,CO + 2\,NO + 3\,H_2O \rightarrow 5\,CO_2 + 2\,NH_3 \tag{3.7}$$

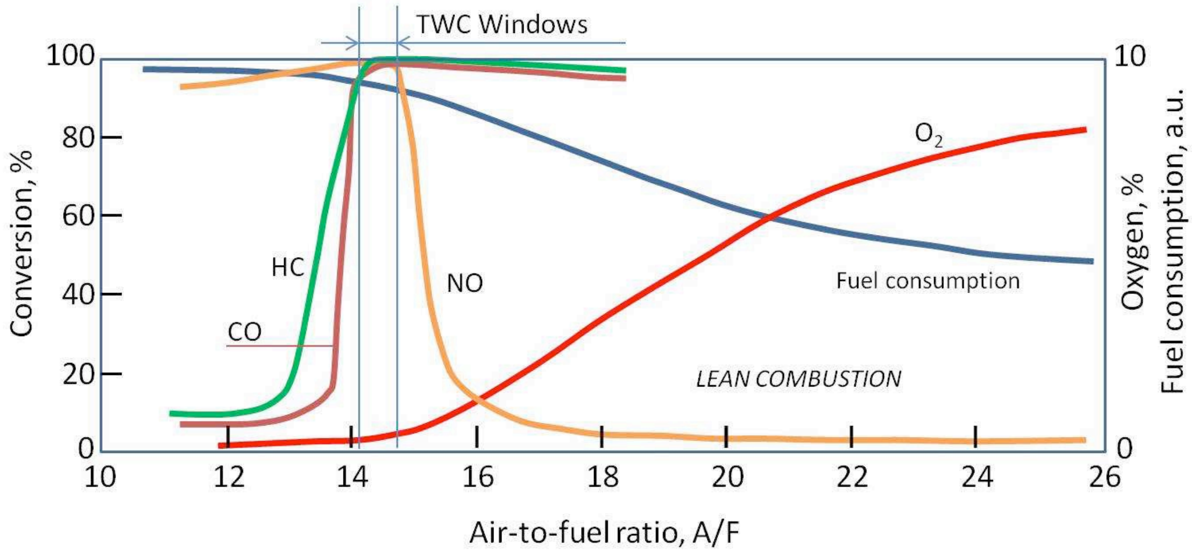


Figure 3.28: Influence of air/fuel ratio (A/F) on the steady conversions of three main harmful components (CO, HC and NOx) in TWC [36]. For pure octane, the A/F ratio at stoichiometric conditions is approximately 14.7 (λ=1).

The TWC also includes ceria compounds that act as an oxygen buffer in order to obtain better conversions throughout the transient engine activities (e.g. accelerations), when deviations from stoichiometric conditions occur [37]. Oxygen is stored under lean conditions (Equation 3.8) and the stored O_2 under rich conditions is released and operated in reaction with H_2, CO and HC(Equations 3.9–3.11). In addition, the redox abilities of CeO_2 also play an important role in shifting water gas and steam reforming reactions (see Eq. 3.12 and 3.13), improving conversions of HC and CO under rich conditions.

$$CeZrO_3 + \frac{1}{2}O_2 \rightarrow CeZrO_4 \tag{3.8}$$

$$CeZrO_4 + H_2 \rightarrow CeZrO_3 + H_2O \quad (3.9)$$

$$CeZrO_4 + CO \rightarrow CeZrO_3 + CO_2 \quad (3.10)$$

$$(2x + \frac{y}{2})\, CeZrO_4 + C_xH_y \rightarrow (2x + \frac{y}{2})\, CeZrO_3 + x\, CO_2 + \frac{y}{2}\, H_2O \quad (3.11)$$

$$H_2O + CO \rightarrow CO_2 + H_2 \quad (3.12)$$

$$3\ H_2O + C_3H_6 \rightarrow 3\, CO + 6H_2 \quad (3.13)$$

3.5.1.2 Oxidation Catalysts

Oxidation catalysts have been used in petrol engine vehicles since the mid-1970s until three-way catalysts have replaced them. They look almost the same as three-way catalysts but slightly less complicated in their structure. Oxidation catalysts convert carbon monoxide (CO) and hydrocarbons (HC) to water and carbon dioxide (CO_2) but have little impact on oxides of nitrogen (NO_x). Because of the efficiency of three-way catalysts, now they are rarely used on petrol-powered vehicles in Europe but are still being used in some of the countries where emission legislation is less rigorous. They are also used on some busses operating on Compressed Natural Gas (CNG), motorcycles and some small petrol engines. However, they are mostly used in the diesel-powered vehicles with the Diesel Oxidation Catalyst (DOC).

Diesel Oxidation Catalysts (DOC)

Diesel oxidation catalyst is mainly used to oxidize CO and unburned hydrocarbon (HC) emissions under excess of oxygen. It is active in NO oxidation as well. However, under fuel-rich conditions the DOC can catalyse water gas shift and steam reforming reactions, which leads to producing H_2. At relatively high concentration levels, water stream and CO_2 are always present in the exhaust fuel. Furthermore, hydrogen has been shown to be the most effective NOx reduction agent in the exhaust fuel [38]. NO oxidation to NO_2 is also known to be a significant step in the process of NOx storage [39]. Due to this, the DOC can therefore enhance the general efficiency of the installed de-NOx system. On the other side, the existence of the DOC may slow down the NSRC's heating during the cold start and the DOC may consume some of the reduction agents from the rich mixture needed for regeneration of the NSRC.
The reducing agents react readily with the abundant O_2 via reactions 3.14–3.15, therefore NOx conversion is very low, and DOC is not a complete solution for the diesel exhaust-gas after-treatment.

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (3.14)$$

$$C_xH_y + \left(x + \frac{y}{2}\right) O_2 \rightarrow x\, CO_2 + \frac{y}{2}\, H_2O \quad (3.15)$$

Most NOx discharging the engine is generally in form of NO, but comparatively high ratios of NO_2/NOx (up to 0.4) are observed in modern diesel engines with lower combustion temperature. In addition, the conversion of NO/NO_2 takes place under oxidizing conditions in the catalyst (cf. Eq. 3.18). At low temperatures, NO_2 is reduced back to NO by CO and HC (see Eq. 3.16 and 3.17), thus in the exhaust gas primarily NO occurs. NO oxidation to NO_2 occurs at greater temperatures (above the light-off for CO and HC reactions with O_2). With increasing temperature, the NO oxidation rate rises, but at the same time the formation of NO_2 is restricted by thermodynamic equilibrium. As a result, in the catalytic converter discharged NO_2 concentration typically shows maximum at intermediate temperatures (see Figure 3.29) [32].

$$NO_2 + CO \rightarrow NO + CO_2 \tag{3.16}$$

$$9\,NO_2 + C_3H_6 \rightarrow NO + 3\,CO_2 + 3\,H_2O \tag{3.17}$$

$$NO + \frac{1}{2}O_2 \rightleftharpoons NO_2 \tag{3.18}$$

The NO/NO_2 ratio plays a significant part in the general behaviour of combined catalytic structures because it affects the catalyst's NOx reactivity that can be situated downstream of the DOC (the NOx storage catalyst — Section 3.5.3, the selective catalytic reduction of NO_x by urea/ammonia— Section 3.5.1.3, and particulate matter oxidation).

Partial reduction of NOx with hydrocarbons under oxygen excess (so-called selective catalytic reduction by hydrocarbons— HC-SCR) also occurs in the DOC (see Eq. 3.19 and 3.20). Nevertheless, it is restricted only to a comparatively small temperature around the hydrocarbon light-off. In addition, under very lean conditions, the NOx reduction selectivity towards undesired N_2O is relatively high (up to 100%). Furthermore, the quantity of hydrocarbons left in the exhaust gas is generally too low to achieve a reasonable NOx conversion.

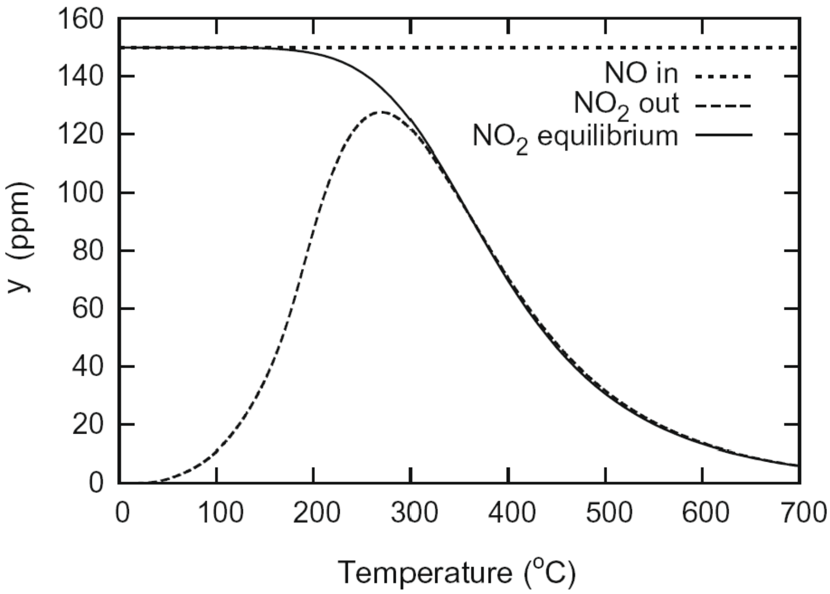


Figure 3.29: Typical dependence of the outlet NOx concentrations on temperature in catalytic converter – influence of thermodynamic equilibrium on NO oxidation. The inlet gas composition: 150 ppm NO, 7 % O_2, 0 ppm NO_2 [32]

$$C_3H_6 + 2\,NO + \frac{7}{2}\,O_2 \rightarrow N_2 + 3\,H_2O + 3\,CO_2 \tag{3.19}$$

$$C_3H_6 + 2\,NO + \frac{8}{2}\,O_2 \rightarrow N_2O + 3\,H_2O + 3\,CO_2 \tag{3.20}$$

The operation of the diesel engine can be altered temporally in order to achieve the rich conditions required to regenerate the NOx storage catalyst. In such cases, to some extent, DOC can also catalyse the typical TWC reactions, such as water gas shift and steam reforming (see Eq. 3.12 and 3.13).

3.5.1.3. Selective Catalytic Reduction (SCR)

Selective Catalytic Reduction (SCR) was firstly implemented on power plants and stationary engines. The SCR of nitrogen oxides in the presence of ammonia (NH_3-SCR) gains significant importance in recent days and became crucial after introducing the Euro 6 emission standards for Diesel engines in Europe. Nowadays is equipped with most new heavy-duty diesel motors (i.e. truck and bus) in Europe and the systems are also being implemented for diesel passenger vehicles and light-duty diesel cars.

There are two main classes of SCR system, defined by the source of the reductant that are being used:

a) hydrocarbons (HC-SCR) and b) NH_3 (NH_3-SCR).

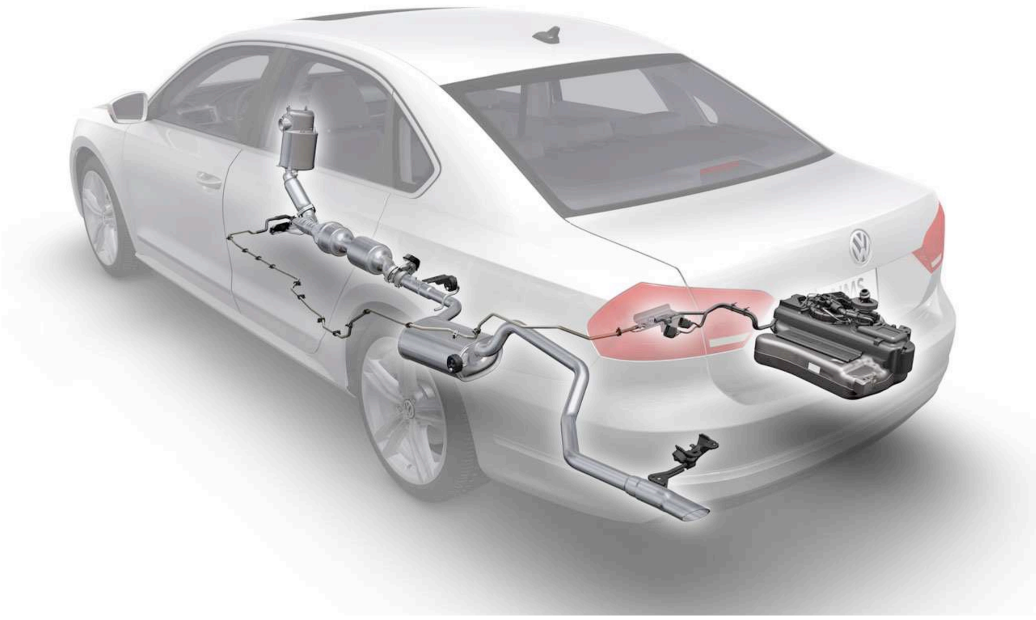


Figure 3.30: NH_3-SCR system in a passenger car. [8]

SCR's effectiveness in reducing NO_x also provides a fuel consumption advantage. It enables developers of diesel engines to take advantage of the trade-off between NO_x, PM and fuel usage and calibrate the engine in a lower area of fuel consumption than if they had to reduce NO_x by engine measures alone. There is also a reduction in particulate emissions and SCR catalytic converters can be used either alone or in conjunction with a particulate filter. [40]

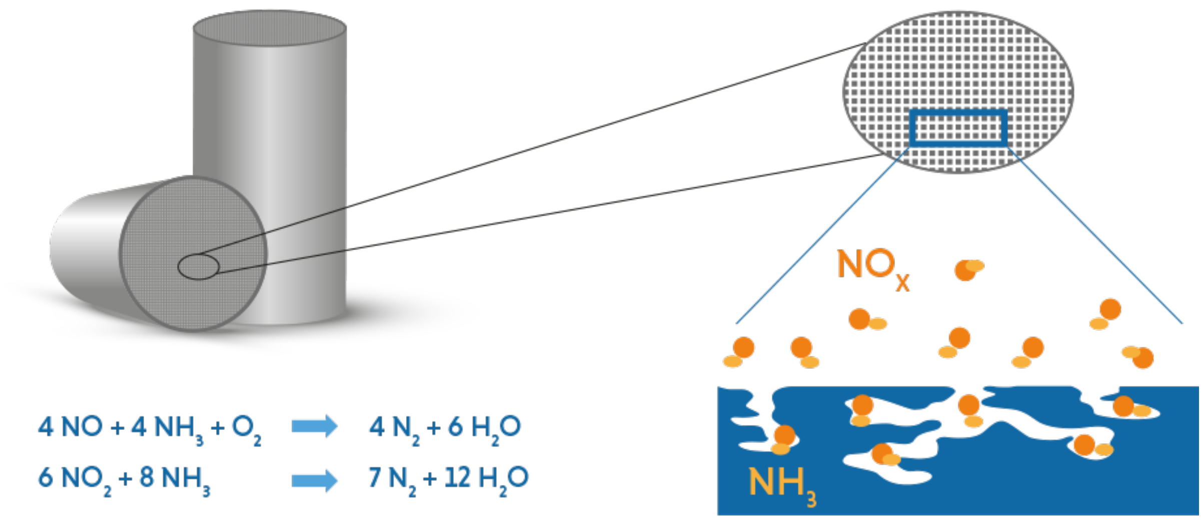


Figure.3.31 Selective Catalytic Reduction [40]

3.5.1.3.1 HC-SCR

Hydrocarbon selective catalytic reduction (HC-SCR) utilizes hydrocarbons to reduce NO_x under oxygen excess. The way of reaction relies on the utilised hydrocarbon; nevertheless, the following equation describes the total reaction in the system:

$$2aNO_x + bHC + cO_2 \rightarrow aN_2 + dCO_2 + eH_2O \quad (3.21)$$

HC corresponds to the hydrocarbon and a, b, c, d and e are the suitable stoichiometric coefficients.

Hydrocarbons used for NO_x reduction either are created from the combustion process (passive control) or are injected before the catalyst (active control), as the concentration of unburned hydrocarbons from modern diesel engines is generally insufficient and not all hydrocarbons are suitable for the NO_x reduction.

Numerous catalyst formulations for the HC-SCR implementation have been tested. Alumina is one of the most effective and stable single-metal oxides that can be used as assistance. Adding single metals, such as copper, cobalt or silver, further promotes its activity. Combination of Ag/Al_2O_3 appears to be a promising formulation for the reduction of NO_x by a variety of hydrocarbons leading mainly to the formation of N_2 [41][42]. Nevertheless, when ethanol is utilised as a reduction agent, as one of the by-products of lean NOx reduction, quite a high quantity of NH_3 (even up to 45 percent in some cases) can be formed. The ammonia created can be further used in the downstream NH_3-SCR catalyst (dual SCR system), thus eliminating need of a secondary tank with the urea solution [43].

Drawback of Ag/AL_2O_3 catalysts is their pure activity at low temperature window. However, adding small amounts of hydrogen to the HC-SCR could dramatically improve these catalysts performance, especially at low temperatures [44][45].

3.5.1.3.2 NH_3-SCR

Selective catalytic reduction of ammonia (NH_3-SCR) utilizes NH_3 to selectively reduce the exhaust gas NOx. This post-treatment system is already being used in power plants and heavy-duty trucks and as well as a diesel passenger vehicles and light commercial vehicles. Cars must be fitted with an additional, periodically re-filled tank containing aqueous urea solution in the automotive application. In the automotive application, the European trade name of this solution is "AdBlue" and contains 32.5% urea weight and 67.5% weight of demineralized water [46][47]. Aqueous urea solution readily hydrolyses to NH_3 at relatively low temperatures (through formation as follows):

$$(NH_2)_2CO \rightarrow NH_3 + HCNO \tag{3.22}$$

$$HCNO + H_2O \rightarrow NH_3 + CO_2 \tag{3.23}$$

Under lean conditions NH_3 then responds selectively with NOx, passing mainly N_2 and water vapour as the final products [49][50][51][52]. Most of the NOx in the exhaust gas is generally in the form of NO but it is possible to significantly improve the reaction rate and low temperature output by having equimolar amount of NO and NO_2 The SCR reaction with NO_2 may also occur in the scheme, but its reaction rate is considerably smaller than Standard-and Fast-SCR response rates.

$$4\,NH_3 + 4NO + O_2 \rightarrow 4\,N_2 + 6\,H_2O\; Standard - SCR \tag{3.24}$$

$$4NH_3 + 2NO + 2NO_2 \rightarrow 4N_2 + 6H_2O\; Fast - SCR \tag{3.25}$$

$$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O\; NO_2 - SCR \tag{3.26}$$

In addition, the NO_2-SCR reaction is not selective to N_2, but a significant amount of N_2O is formed as a by-product through the formation and subsequent decomposition of ammonium nitrate [52]:

$$2\,NH_3 + 2\,NO_2 \rightarrow N_2 + NH_4NO_3 + H_2O \tag{3.27}$$

$$NH_4NO_3 \rightarrow N_2O + 2\,H_2O \tag{3.28}$$

The amount of N_2O formed depends on the temperature (usually with a maximum of 250–350° C), catalyst type and on the ratio of NO_2/NOx (N_2O generation increases with an excessive NO_2 content in the feed mixture). [50]

Located upstream of the SCR catalyst, diesel oxidation catalyst (DOC) may boost the NO_2/NO equimolar ratio, which is ideal for quick SCR [53]. NH_3-SCR output is also heavily dependent on the dosage of urea/ammonia. Too little urea injected into the system outcomes in low NOx conversion, while too much urea added to the system can contribute to the undesirable atmospheric slip of NH_3 [54][55]. Therefore, optimizing the approach for urea dosing under transient driving cycle conditions remains a significant challenge for the NH_3-SCR.

The disadvantages of using urea solution in NH_3-SCR are the need for an additional storage tank, an injection unit and heating system, restricted urea solution stability, strong deposit formation and complete system treatment [47].

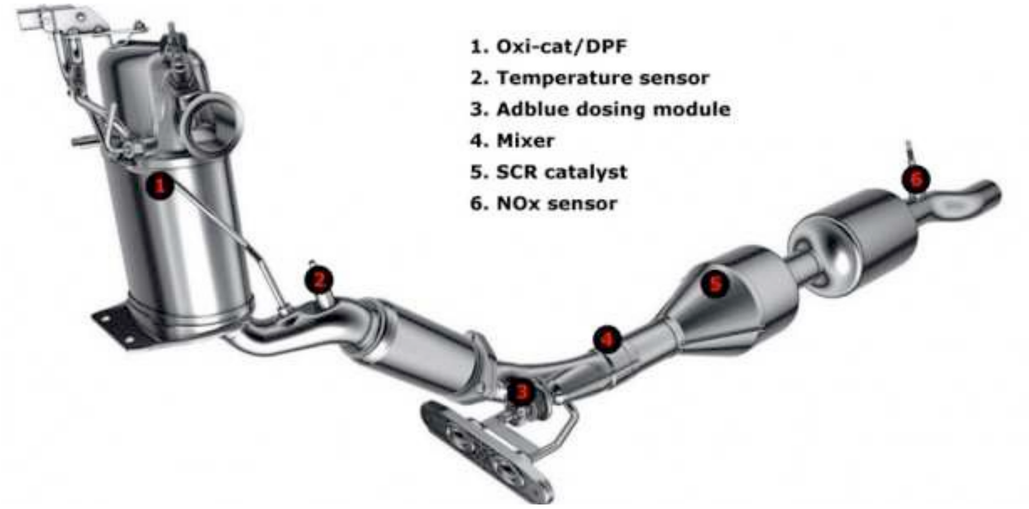


Figure 3.32: *Scheme of the SCR system in a passenger vehicle* [8]

AdBlue® is a stable, non-flammable, colourless liquid comprising 32.5% urea that is not categorized as dangerous to health and requires no unique precautions for handling. Urea is used as an artificial fertilizer and it is produced to norms that are internationally recognized. The consumption of AdBlue® is typically 3-4% of fuel consumption for a Euro 4 engine, 5-7% for a Euro 5 engine, and 3-5% for a Euro 6 engine, depending on driving, load and road conditions. A truck can have an AdBlue® tank, which will hold enough urea to last for up to 10000 km [40].

Figure 3.33: The fluid cleans diesel exhaust fuels and effectively converts it into harmless water and nitrogen that is exhausted. [40]

With the introduction of Real-Driving Emissions (RDE), SCR are often used to regulate NOx emissions for diesel passenger cars and light commercial vehicles. The vehicle manufacturer has to find a compromise between the size of the urea tank and the refill intervals. Typical AdBlue® consumption of early Euro 6 cars were around 1l/1000 km on a light-duty vehicle. Manufacturers of vehicles expect it to increase to 2-3.5 l/1000 km when a 1.5 NO_x Conformity Factor comes into force - the conformity factor of 1.5 is defined as 1 (i.e., the laboratory NO_x limit) plus a margin of 0.5 that represents the uncertainty/error of PEMS instruments, to be reduced if PEMS technology is improved). The average size of the urea tank is 10-17 litters for vehicles and vans. On-board systems warn the driver when the urea tank has to be filled. [40]

3.5.2. Filters

Particulate filters in general are used with diesel engines to remove diesel particulate matter (PM), but also, they can be used with in direct injection petrol engines, which are also considered with a large number of ultrafine particles in the exhausting fuels.

3.5.2.1 Diesel Particulate Filters (DPFs)

Most of today's diesel-powered vehicles are equipped with diesel particulate filters (DPF) in order to control the soot particles emitted by the diesel engines. DPF materials have been advanced that show excellent filtration efficiencies, in addition of 90%, as well as great mechanical and thermal stability. They have become the most effective technology for the regulation of diesel particulate emissions, as well as particle mass and numbers. [56]

DPFs are most efficient in regulating the solid fraction of diesel particulates, including elemental carbon (soot) and the related black smoke emission, due to the particle deposition processes in these systems. DPFs may have restricted or might be completely ineffective in regulating non-solid fractions of PM emissions— the organic fraction (OF) and particulates of sulphate. In DPF systems is likely to be add extra functional components targeting the OF — typically oxidation catalysts in order to control total PM emissions, while ultra-low sulphur fuels may be needed to control sulphate particulates. [56]
However, as soot particles accumulate, the filter may become obstructed (see Figure 3.34). The burning of the accumulated particulates requires active control.
If oxygen is used as an oxidizer, a significant increase in temperature is required. This regular process is often referred to as active regeneration. Another type of the DPF regeneration is continuous soot oxidation by nitrogen dioxide. [57].

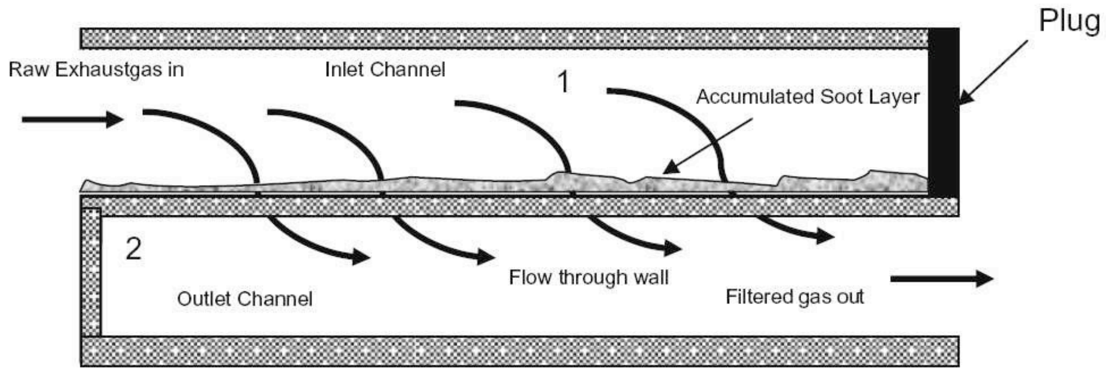


Figure 3.34: Scheme of the channel construction of a particulate filter. The gas enters the monolith through the open frontal channels and is then blocked by the closed outlet opening. This forces the gas to pass through the wall of the monolith, resulting in trapping of the particulate matter in the monolith. [58]

The NO_2 is created from NO through an oxygen reaction. This response is quicker in the presence of oxidation catalysts and raises the NO_2 ratio in NOx, which referees to 5-15 % at the outlet of the combustion chamber. See Table 3.5 for a full description of the considered responses and their reaction rates. Several articles are accessible (e.g. [59], [60]) and have defined mathematical modelling of diesel particulate filters and experimental observations of the process (e.g. [61], [62]).

A DPF device requires a trap and a system to regenerate the trap, otherwise the trap will be blocked by particles and the backpressure will increase. During (thermal) regeneration, the filter must hold the conditions that occur.

While DPFs with pore size of down to 50 nm are commercially accessible for liquid filtration, and it is not helpful to use them for gases due to their exceptional pressure drop. DPF materials with big pore sizes are well known for filtering tiny particles not as a sieve but in other ways, such as impaction and diffusion ("deep-bed filtration") — see Fig. 3.35). For instance, High-Efficiency Particulate Air (HEPA) filters consisting of fiber felt are used to clean gases/air. Throughout filtration the collected particles can improve collection effectiveness through the so-called" Cake-filtration" impact (Fig. 3.35).

It is also essential to consider the impacts of detaining particles in contrast to a sieve. Collecting and detaining particles (aside from particles size, pore size and filter thickness) are mainly influenced by gas/particles velocity. Consequently, a moderate velocity of exhaust gas must be obtained through the filter. A specified exhaust volume of the engine at full power generates a very high gas velocity in small-diameter channels, which can only be reduced by a high cross-sectional area of the filter geometry.

It should be noted that PM filters also function as a muffler and can therefore fully or partly replace the sound-absorbing system, often using very limited underfloor space in vehicles.

Regeneration

Accumulated particles develop filter pressure drop. This is why the filter needs to be cleaned, which is generally achieved by thermal means. Soot begins burning spontaneously above 6001°C or is further promoted by catalysts at temperature around 300–4001°C (traces of Fe, Cu, or Ce). However, even such temperatures are not often accessible in the exhaust pipe; it is necessary to use technical means to control the regeneration of the filter. [63]

At normal exhaust temperatures, trapped particulates burn off using the strong oxidative characteristics of NO_2 and can burn in oxygen when the exhaust gas temperature is periodically increased by post-combustion. The most effective regeneration techniques include:

- Incorporating an oxidation catalyst upstream of the filter that, as well as operating as a conventional oxidation catalyst also increases the ratio of NO_2 to NO in the exhaust.
- Incorporating a catalytic coating on the filter to lower the temperature at which particulate burns
- Using very small quantities of fuel-borne catalyst, such as ceria or iron additive compounds added to the fuel thanks to an on-board dosing system. The catalyst, when collected on the filter as an intimate mixture with the particulate, allows the particulate to burn at lower exhaust temperatures (around 350°C instead of 650°C) and increases the combustion kinetic (typically 2-3 minutes) while the solid residues of the catalyst are retained on the filter as ashes.
- Place a fuel injector in the exhaust line upstream of the DPF.
- Electrical heating of the trap either on or off the vehicle.

However, without the use of additives, electric heaters or gas burners can produce high temperatures. By means of motor management (post-injection) and an oxidation catalyst in front of the filter, the exhaust temperature can also be raised up to more than 4001°C to ignite the soot [63]. The filter needs a special catalyst coating for such systems, or the soot has to be enriched with fuel additives (so-called fuel-borne additives). Due to exothermic soot oxidation, local temperature increases after ignition depending on thermal properties of the filter material (heat capacity and conductivity) as well as the amount of exhaust and temperature. It is the worst case to stop the engine in a fully charged trap after the soot has been ignited. Then 10001°C or higher temperatures may occur locally in the filter.

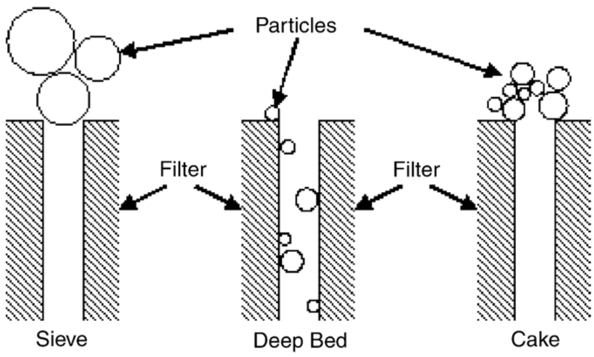


Figure 3.35. Modes of filtration (after[5]) [63]

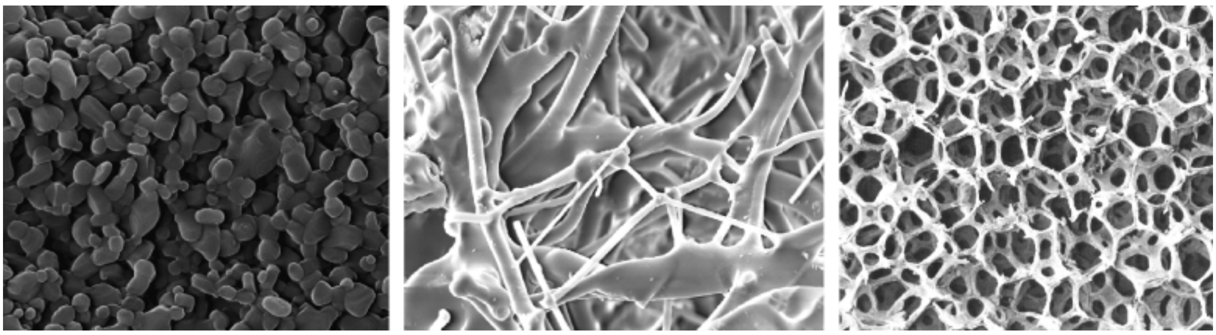


Fig. 36. Porous ceramic structures which can be used for particle filtration made of sintered powder (on the left), fibers (in the middle), open celled foams (on the right). Structure sizes can be different and are described in the text [63]

Ash Storage

No fuel substances stay in the filter after regeneration. They come from fuel additives, oil, salts from environmental air, motor wear, and consist mainly and consist mainly of oxides, sulphates and phosphates of zinc, calcium and iron. Ash accumulation contributes to increased pressure drop and filter capability deterioration, which limits the filter's lifetime. A filter material must also withstand the chemical interaction at high temperatures with the ashes, which will also occur during regeneration.

Filter Materials

Pore (size, quantity, and shape) and filter thickness are accountable for filtration effectiveness as well as pressure drop and material strength. It is possible to use very distinct structures such as those made of sintered powders, short fiber felts or knitted /weaved long fibers and open-celled foams (Fig. 3.36).

Pressure drop and permeability

In addition to high filtration effectiveness, the primary requirement on the filter is low pressure drop. Darci's Law and Forchheimer's Extension (Equation 3.29) describe the pressure drop of a gas (or fluid) flowing through a porous material. Specific permeability k and inertial coefficient b are a porous material's specific properties. The Forchheimer's Extension can be neglected for low gas velocities.

$$\Delta p = \frac{\eta}{k} dv + \beta \rho d v^2 \qquad (3.29)$$

where Δp is the pressure drop (Pa), η the dynamic viscosity (Pa · s), k the specific permeability (m^2), d the thickness (m), v the gas velocity ($m \cdot s^{-1}$), β the inertial coefficient t (m^{-1}), ρ the gas density ($kg \cdot m^{-3}$).

A porous material's permeability depends primarily on the size of the pore, the volume of the pore, and the shape of the pore. There are many distinct and complex models trying to calculate the permeability. The Ergun's equation (Equation 3.30) can make a rough estimate.

Permeability varies from about $10^{-12}\ m^2$ (wall flow filter) to $10^{-9}\ m^2$ (fiber or foam filter) for ceramic materials used as DPF.

$$k = \frac{\varepsilon^3}{150(1-\varepsilon)^2} D^2 \qquad (3.30)$$

ε is the porosity (-), D is the pore diameter (m)

The entire filter system's flow resistance is also largely influenced by some other factors. Losses of inlet and outlet (contraction and expansion) contribute to the drop-in pressure and channel friction in the wall-flow filter type of DPFs. During operation, the pressure drop rises by the growing filter accumulation in the pores or on the surface of the material.

Regarding to material selection, material should have high temperature stability, thermal strain resistance, corrosion stability and sufficient mechanical strength to meet all filtration, regeneration and system application requirements. It should have a low Young's modulus, low thermal expansion coefficient (CTE) and good thermal conductivity to reduce thermal stress effects. Considering all common substances of materials, there is no material that perfectly addresses all of these demands. Table I shows a selection of applicants comparing pure (dense) material properties. The properties of the various filter materials can only be directly compared if they have the same pore volume and mean pore size. Most of the materials are made of a thin-walled honeycomb shape that cannot be measured by common standards with good accuracy, and most of the filters differ in cell size and wall thickness of the honeycomb and cannot be correctly compared. [63]

Material	Cordierite	SiC	Silicon	Mullite	Al-Titanate	FeCrNi
Density (g/cm^3)	2.1	3.1–3.2	2.33	2.9	3.3	8.1
Thermal conductivity (RT) (W/mK)	1–3	90	120	4–5	1.5–3	14
CTE 20–1000°C (10^{-6} 1/K)	0.9–2.5	4.7–5.2	4.4	4.4	−0.5–3	17
Young's modulus (GPa)	130	410	110	150	20	200
Thermal limit for application (air) (°C)	1350	1500	1350	1600	1500	1250
Corrosion resistance*	−	+	o	o	o	−
Price*	++	−	−−	+	+	−−

*These properties cannot be compared directly. A rough estimation gives: ++, very good; +, good; o, ambient; −−, negative, −− very negative.

*Table 3.10 Material Candidates for Diesel Particulate Filters; Properties are of pure (Dense) materials. Note that high amount of porosity will change thermal conductivity, young's modulus and strength drastically. [*8*]*

Figure 3.37: *An opened DPF from a light commercial vehicle. [9]*

3.5.2.2. Particulate wall-flow filters

Physical filtration in wall-flow filters removes particulate matter from the exhaust using a honeycomb structure similar to an emission catalyst substrate but with the channels blocked at alternate ends.

Therefore, the exhaust gas is forced to flow between the channels through the walls and the particulate matter is accumulating on the walls as a soot cake. Such filters are produced from ceramic honeycomb products (cordierite, silicon carbide or titanium aluminium) (see Fig. 3.38) [40].

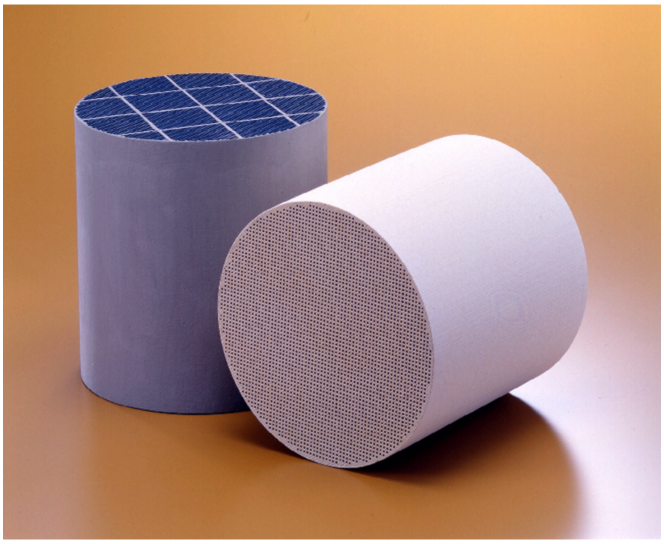


Figure 3.38 Wall-flow particulate filters made ceramic honeycomb products [40]

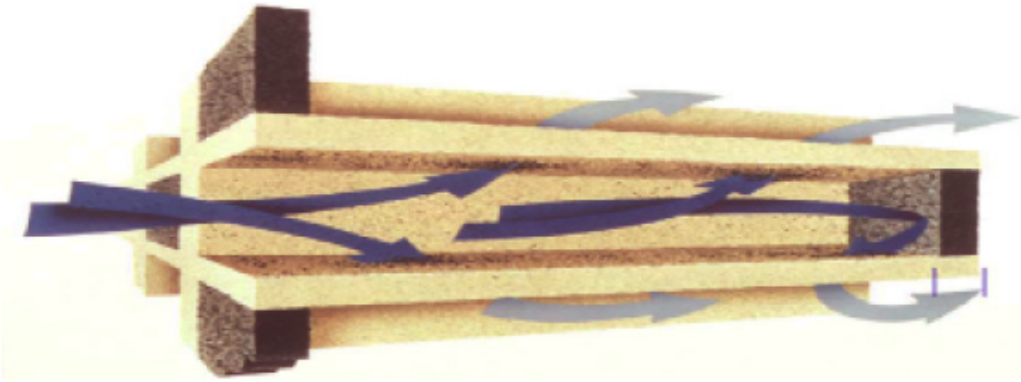


Figure 3.39. *Wall-flow filters trap most ultra-fine exhaust particulate [40]*

Ceramic wall-flow filters remove almost entirely the carbon particulates, including fine particles with a diameter of less than 100 nanometres (nm) with a mass effectiveness of > 95percentage and a number of > 99percentage over a wide range of engine operating conditions. The recent European emission standard values (i.e. Euro 5 and 6) are set on both mass and number to account for the amount and size of particulates, which are considered to be more critical health effect indicators. "AECC test programmes show that both Diesel Particulate Filters (DPF) and Gasoline Particulate Filters (GPF) gave real-world PN emissions below a Conformity Factor of 1.0 under the conditions tested". [40]

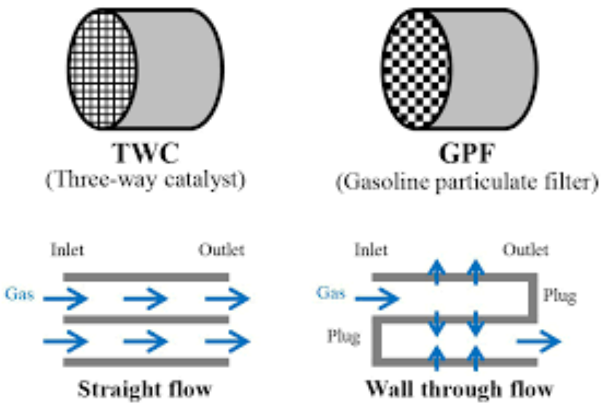


Figure 3.40 Comparison between TWC and GPF gas flow through the channels [*40]*

3.5.2.3. Gasoline Particulate Filter (GPF)

Gasoline particulate filters (GPF) are an after-treatment emission technology based on DPF designed to regulate particulate emissions from petrol direct injection engines (GDI). GDI is a main petrol engine technology designed to decrease CO_2 emissions while improving performance and torque. However, the population of GDI cars has increased, driven by demands for CO_2 and/or fuel economy. An approximately 2/3 of Europe's new petrol vehicles were GDI in 2016. [64]

Most of the GDI particles are formed during the cold-start phase, catalyst heating mode and dynamic motor modes. As a result, the injection system including the injection-operating program (e.g. number of injections, timing, and injection amount) was further developed to improve air-fuel mixture in the cold-start phase. In addition, internal engine measures such as enhanced homogenization of the mixture and minimized quantity of injected fuel hitting the walls helps to prevent particle formation. Thus, the recent GDI automobiles on the statutory test cycle (NEDC or WLTC) can reach the PN limit of 6×10^{11}/km. However, in a wide range of engine map operations, the RDE method also involves particle counting. The technology of GPF was obtained from good experience with DPF; it guarantees ultrafine particle control under real-world driving circumstances from Gasoline Direct Injection engines.

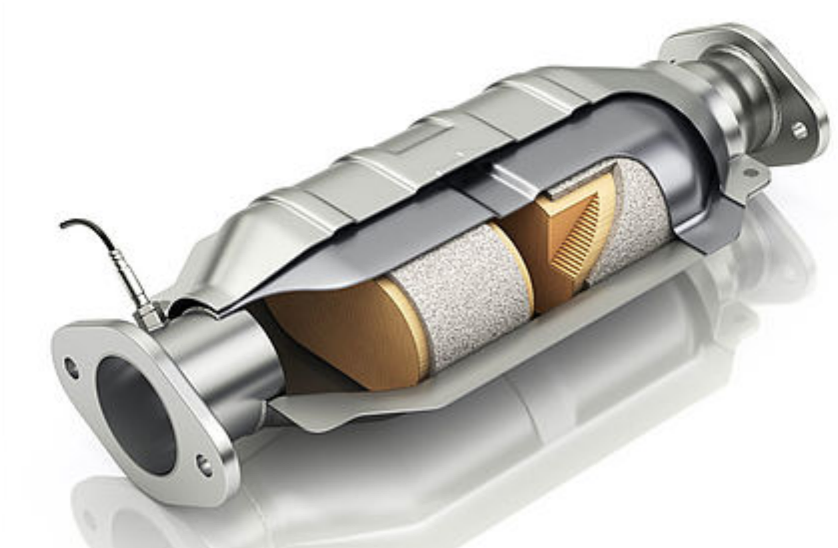


Figure.3.41 An opened Gasoline Particulate Filter (GPF) from a light commercial vehicle [64]

GPFs are anticipated to be used mainly in the European Union and China to satisfy the particle number (PN) emission standards enacted in both regulations for gasoline passenger cars and light commercial vehicles. The Euro 6 regulations both efficient as of September 2017 for GDI's set PN (as well as PM) limits equal to those for diesel vehicles. (see section 3.5.1.2).

The above requirements could also be met—at least in certain types of vehicles— through in-cylinder controls such as fuel injection strategies, without particulate filters. However, the GPF has several advantages compared to in-cylinder controls:

- Effectiveness under all operating conditions—while in-cylinder strategies tend to be more effective under certain modes of operation, the GPF provides PN emission control under all engine operating conditions—an advantage that is especially important in RDE testing.

- Control of emissions from engine faults—Increased PN emissions can occur because of engine faults and malfunction, such as increased lube oil consumption. Particulate filters can effectively control these emissions. *[65]*
- Control of unregulated emissions—The GPF can control certain unregulated emissions, including polynuclear aromatic hydrocarbons (PAH). However, GDI engines, even though equipped with TWC, may produce significant levels of toxic PAH emissions [65].

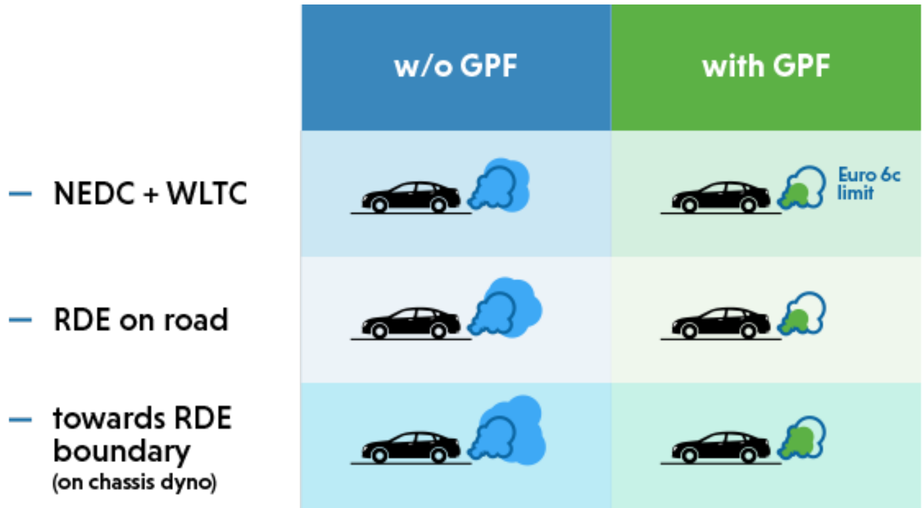


Figure. 3.42. Illustration of vehicle without and with Gasoline Particulate Filter (GPF) measured in different driving cycles [66]

Most early GPF applications included an uncoated GPF positioned downstream of a TWC catalyst. As the technology matured, GPFs have been also covered with a three-way catalyst. This setup of catalyst-coated GPF is sometimes referred to as the four-way catalyst. The 1.0 TSI engine used in the 2018 VW "Up!" was one of the early applications of a coated GPF. [66]

While GPF and DPF technologies are closely related, there are a number of differences in filter configuration, operation and control strategy due to operating conditions differences, particulate emission rates, and as well as the composition between diesel and gasoline engines.

3.5.3 NO_X storage and reduction catalyst (NSRC)

Another method that can be used to minimize NO_x emissions from diesel engines as well as petrol engines is the NO_x storage and reduction catalyst (NSRC). The catalyst concept for NO_x storage and reduction has been designed for automobiles equipped with lean-burn engines where excess of oxygen obstructs the reduction of NO_x emissions and common three-way catalysts cannot be used. This is characteristic for diesel-powered vehicles. The NSRC operation principle is based on periodic lean/rich cycling. The NO_x is adsorbed on the catalyst surface during the lean period (within a few minutes), while the remaining NO_x is desorbed during the rich period (within a few seconds) and reduced by a temporary excess of reductants resulting from the fuel mixture enrichment (CO, H_2, HC).[cf. 67, 68].

3.5.3.1. NO_X-storage and reduction kinetics

A reactor with NO_X-storage capacity must be run periodically by switching between lean conditions (oxygen excess) and rich conditions (reductants excess) [69, 70]. The engine control unit controls this switching. Nitrogen oxides are adsorbed on the catalyst surface during the lean phase (mainly in the form of $Ba(NO_3)_2$) and oxygen is stored on the catalyst surface [68,70].

The rich phase needs to be applied after the catalyst surface is saturated in order to remove and reduce the stored nitrogen oxides from the surface, preferentially to harmless nitrogen and water.

Nitrogen oxides may be reduced (depending on conditions) to NH_3 during the rich phase [38]. The second catalytic layer can capture this ammonia and use it even during the consequent lean phase to reduce the nitrogen oxides [71, 72]. It has been observed that higher NO_2 content in the inlet NOx mixture enhances the NOx storage in NSRC, particularly at lower temperatures [73].

CHAPTER 4

4. METHODOLOGY AND MEASUREMENTS

The previous chapters have seen a theoretical explanation of the global environmental impact of energy conversion, as well as emission formation and emission legislation in the European Union (EU) for modern vehicles in specific, as well as driving cycle's measurements. Furthermore, they emphasized new and current implementation developments for further reduction of the unwanted products of the combustion engines. Now the introduced theoretical concepts shall be applied to the example of data collected from various sources to research the progress, trends and the forecast of emissions from road transport. Moreover, the methodology will characterize the background materials used, such as datasets so that the reader can assess the significance of these and make value of the final results and conclusions.

4.1. Research Questions

The following research questions were formulated:

1. What are the annual greenhouse gas emissions, main emission components and main pollutants from the road transport?
2. Does the EU remain on track to reach its targets in the future?
3. Which method should be used for the most efficient emissions reduction in passenger cars?

Following the above-mentioned research questions; the thesis tries to evaluate three main research parts. Firstly, this research paper tries to understand emission from the modern vehicles, development and emission standards with a specific focus on after-treatment legislations in EU; current technology control and measurements of the emissions and if these technologies are sufficient for reaching the targets. Lastly, the question was raised what is the best solution that the manufacturers need to follow in order to reach the EU target for emission reduction?

For answering the first question, the development of global greenhouse emission with various forms of investigation and the main emission components from road transport and their evolution over time will be explained. In this regard, the overview of air quality in the EU with a focus on road transport and passenger vehicles pollutants will be analysed. Sourcing and statistics of main pollutants will be highlighted as well and the various reasons that stand behind the pollution.
The second research question investigates the EU's emission targets towards better air quality strategy and global development for better sustainability. This includes the explanation of EU's standards of emissions in the future, forecast, trends and predictions of EU's emission from the passenger vehicles. In addition, the average pollution of selected car brands in the EU member states will be explained, as well as the question if the manufacturers are ready and are aiming for further emission reduction of their vehicles. Lastly, the focus will be on selected examples on how to further reduce emissions. Before going into detail, new technologies and alternatives must be briefly explained and analysed with the main aim why automobile companies need to switch their technologies into other alternatives and as well as other factors influencing the pollution problem, such as urban mobility and energy sources for vehicle production. The methodical approach to answering the above-explained research questions will be shown in the following section on methodology.

The research questions include an external approach and analysis of the theoretical framework and research literature as well as an internal approach, which requires the active involvement of the researcher into running analyses and forecasting trends and predict related topics of the emissions from the road transport and modern cars.

4.2. Location analysis

The location of this research is within the EU and some of the cooperation countries of the European Environmental Agency (EEA), which most of the data was taken from and analysed. Europe as a whole is not taken into consideration in the data because many non-EU countries have different emission legislation and restrictions.
All member states within the EU observe the same emission standards from internal combustion engines. The EU currently has 28 state members, which joined as follows:

- 1958: Belgium, Germany, France, Italy, Luxembourg, the Netherlands
- 1973: Denmark, Ireland, the United Kingdom
- 1981: Greece
- 1986: Spain, Portugal
- 1995: Austria, Finland, Sweden
- 2004: Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia
- 2007: Bulgaria, Romania
- 2013: Croatia

However, the EEA, which is an agency of the European Union to help the community, member and cooperating countries make informed decisions about improving the environment, integrating environmental considerations into economic policies and moving towards sustainability as well as coordinate environmental information on Europe. The EEA currently consists of 33-member countries and 6 cooperating countries. The 33-member countries are the 28 European Union member states, together with Iceland, Liechtenstein, Norway, Switzerland and Turkey. The six cooperating countries are Albania, Bosnia and Herzegovina, North Macedonia, Montenegro, Serbia and Kosovo*. Main clients are the European Union institutions — the European Commission, the European Parliament and the Council.

*Figure 4.1. Member countries (green) and Cooperation countries (blue) *The designation is without prejudice to position on the status and the opinion on the Kosovo Declaration of Independence.*
source: [Stojchevski 2019 after EEA]

4.3. Data Collection

To answer the relevant questions and evaluate outcomes and as well as to summarize this research, secondary data was gathered and measured from several databases. The datasets were taken from three main data providers for environmental analysis, statistics and data science research.
Most of the data was collected from the "European Environmental Agency" (https://www.eea.europa.eu/) datasets and "Statista" a German online portal for statistics. According to the company, its platform contains more than 1,000,000 statistics on more than 80,000 topics from more than 22,500 sources (https://www.statista.com). The first website displays highly reliable data as it is steered by EU Member Government and European Union agencies. Second data source provides a plethora of international data selected from scientific journals, official communications, trade reports etc. However, they are only pooling datasets and the actual data source must be always investigated for its reliability.

The following datasets were used in this research and observed for the analysis, forecasts, trends and predictions of the emissions from road transport and modern cars:

a) *Greenhouse Gas Emission from transport in EU (not Avion and not maritime included in this dataset)*
This data was taken from the EEA official website datasets for greenhouse gas emission from road transport from the year 1990–2017.The annual official data submission is

made by the EU Member States to the United Nations Framework Convention on Climate Change (UNFCCC) and the EU Monitoring Mechanism Regulation (MMR). The compilation of emission estimates by Member States is based on a combination of sectoral activity data, calorific values and carbon emission factors. Recommended methodologies for the estimation of emission data are compiled in the IPCC (Intergovernmental Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories, supplemented by the 'Good Practice Guidance and Uncertainty Management in National Greenhouse gas Inventories' and UNFCCC Guidelines. However, the data was standardized and broken up into respective parts, then fitted in the research with only the emission from the road transport, where emission from the aviation and maritime are not included in the analyses. The data shows total greenhouse gas emissions from transport, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).
Data Published 22 Nov 2018.
Data Source: [74]

b) *Air pollutant emissions data (Gothenburg Protocol, LRTAP Convention) 1990-2017; Main Pollutant Components from the road transport 1990-2017*
This data was taken from the EEA official website datasets for air pollutant emissions from the year 1990–2017. However, the data was standardized and broken up into respective parts, then fitted in the research with only the main pollutant components from the road transport, such as emissions of nitrogen oxides (NO_x), carbon monoxide (CO) emissions and ammonia (NH_3) and as well as fine particulate matters $PM_{2.5}$ and PM_{10}. The Convention on Long-range Transboundary Air Pollution (LRTAP) data reports and tracks the emissions of key air pollutants over the past years. It is submitted by the EU to the UNECE under the requirements of the Gothenburg Protocol to the LRTAP Convention, which aims to limit, and as far as possible, gradually reduce and prevent air pollution for 2020 and beyond.
The Gothenburg Protocol entered into force on 17 May 2005.
Data published 22 July 2019.
Data Source: [75]

c) *Monitoring of CO_2 emissions from passenger cars - Data 2018*
This dataset was taken from the EEA official website where the regulation (EC) no. 443/2009 requires member states to record information for each new passenger car registered in its territory. Every year, each member state shall submit to the European Commission all the information related to their new registrations. In particular, the following details are required for each new passenger car registered: manufacturer name, type approval number, type, variant, version, make and commercial name, specific emissions of CO_2 (NEDC and WLTP protocols), masses of the vehicle, wheelbase, track width, engine capacity and power, fuel type and mode, eco-innovations and electricity consumption. The data for EU-28 are reported in the main database. Since 2018, Iceland is also included in the database. Data published 24 June 2019 — Last modified 26 August 2019.
Data Source: [76]

d) *DE:Grenzwerte für den CO_2-Flottenausstoß bei Neuwagen von Automobilherstellern in der Europäischen Union im Zeitraum der Jahre 2015 bis 2030*

EN: Limit values for CO_2 emissions of new cars from car manufacturers in the European Union in the period from 2015 to 2030
This data was taken from the www.de.statista.com website. The actual source is from the German Association of the Automotive Industry (VDA). The data taken is published in German which caused difficulties regarding translating some of the words and parameters into English. The data gives the average values of CO_2 emissions of new cars that use fossil fuels and shows that the highest emission values are for private transport. When considering the greenhouse gas emissions of passenger transport in Germany, passenger cars are by far the biggest polluters. The most climate-friendly cut here was the railway. After the automotive industry succeeded in significantly reducing its total carbon dioxide emissions since the end of the 1990s, emissions have risen slightly again in recent years. The European Union has therefore set a maximum value of 61.75 grams per kilometre for the year 2030 as the limit for automobile exhaust gas emissions.
Last updated: 11. October 2018
Data Source: [77]

e) DE: Durchschnittlicher CO_2-Ausstoß der in Europa neu zugelassenen Pkw ausgewählter Marken in den Jahren 2011 bis 2018 (in Gramm pro Kilometer)

EN: Average CO_2 emissions of newly registered passenger cars of selected brands in the years 2011 to 2018 in EU (in grams per kilometre)
This data was taken from the www.de.statista.com website datasets and the dataset is in German. The actual source is from Jato.com website. Car Comparisons & Automotive Market Research – JATO, it is a global automotive business intelligence and it provides data for analysis market trends, vehicle specifications, car pricing and more. The data shows the comparison of passenger car inventories in European countries for 18 car brands. In particular, heavy vehicles and vehicles with high horsepower engines have high CO_2 emissions. These include luxury and off-road and sports cars. Alternative drives clearly are an advantage. Diesel-powered vehicles emit slightly less carbon dioxide on average than petrol-engine vehicles. Alternative drives are significantly more climate-friendly than conventional burners. The average emissions of CO_2 in newly registered passenger cars with natural gas, electric or hybrid engines in Europe only burn about half that much.
Last updated 09. August 2019
Data Source: [78]

The gathered data was analysed in Python 3, which is one of the most used programming languages for Data Science and Analytics. Most of the data taken from the sets mentioned was raw data. In order to make the data compilable for the analysis, several steps of data tidying and validation were firstly performed. More information for the steps of the data analysis and compilation are mentioned in the following Section 4.4.

4.4. Data Analysis and Compilation

After gathering the information and field research, the raw data must be compiled so that the analysis can be performed, and data can be broken down into respective parts and segments.
Data analysis and compilation also includes data cleaning and tiding strategy before further analysis is performed. This cleaning is validating the data for errors or irrelevant data. It is a separate process for data cleaning performed before the analysis, which is very important to

fetch desirable results. This process also includes determining the missing values and inputting the most appropriate values in place.
This compilation of the raw data mentioned above and the further analysis of the already cleaned data were coded in Python 3. It is a very powerful language when it comes to data sciences and analytical operations, with its libraries such as Pandas and Numpy, which is one of the data-centric python packages that makes importing and analysing data much easier. Pandas is built on Numpy and Matplot, which makes data manipulation and visualization more convenient. Several examples of data approaching and cleaning that were made for the aim of this research are shown in Figure 4.2 and as well on the following figures from this chapter.

****PM10 concentration 2017****

```
In [ ]: #PM10 measurements at station level in 2017

In [31]: #EU daily limit value for particulate matter < 10 µm (PM10): not more than 35 days/year with a daily mean concentratio
n exceeding 50 µg/m3

In [32]: #AirPollutionLevel corresponds to the 36th highest daily mean concentration

In [1]: import pandas as pd
import numpy as np
import seaborn as sns
import matplotlib.pyplot as plt
%matplotlib inline

In [2]: apc = pd.read_excel('PM10.2017 data -EU values.xlsx')

In [3]: apc.head()
```

Out[3]:

	Country	City	AirQualityStationEoICode	AQStationName	AirPollutant	AirPollutionLevel	UnitOfAirpollutionLevel	AirQualityStationType	AirQualityStationArea
0	Montenegro	NaN	ME0001A	Pljevlja	PM10	228	ug/m3	Background	urban
1	Turkey	NaN	TR760141	IGDIR	PM10	221	ug/m3	Background	urban
2	Turkey	NaN	TR810141	DUZCE	PM10	206	ug/m3	Background	urban
3	The former Yugoslav Republic of Macedonia	NaN	MK0031A	Lisice	PM10	200	ug/m3	Industrial	urban
4	Turkey	NaN	TR380131	KAYSERI-HURRIYET	PM10	189	ug/m3	Traffic	urban

Figure 4.2. Example of raw data cleaning and selecting for PM_{10} concentration data taken from the EEA website [Stojchevski]

Figure 4.2 indicates a PM_{10} concentration example of how data cleaning and selecting was done. It shows the needed libraries for the data modification as well as analyses that were made for the research for the raw data provided from the EEA website, thus eventually the needed final results and visualisations can be shown for the aim of this thesis. The figure explains the concentration for Europe including 33 countries which will be shown in the result section. It includes the overall PM_{10} concentration from the three sectors: Background, Industrial and Traffic. However, in this thesis, the focus is on the pollutants from the vehicles. Accordingly, the data was split and broken up into respective parts, then fitted in the research with the PM_{10} pollutant from the traffic sector only.
Data sampling is also one more distinguished approach to decrease the probability of repetitive data elements. It includes creating subsets of information according to a specific variable value and managing them as a whole. The more relevant the data, the more accurate the results are (Figure 4.3).

```
In [7]: #dropping some of the unnecessary columns

In [8]: apc.drop(['City','AirPollutant','UnitOfAirpollutionLevel', 'AirQualityStationEoICode'], axis=1, inplace=True)

In [9]: apc.head()
Out[9]:
```

	Country	AQStationName	AirPollutionLevel	AirQualityStationType	AirQualityStationArea
0	Montenegro	Pljevlja	228	Background	urban
1	Turkey	IGDIR	221	Background	urban
2	Turkey	DUZCE	206	Background	urban
3	The former Yugoslav Republic of Macedonia	Lisice	200	Industrial	urban
4	Turkey	KAYSERI-HURRIYET	189	Traffic	urban

```
In [10]: # removing The former Yugoslav Republic of Macedonia to North Macedonia

In [11]: apc['Country'].replace({'The former Yugoslav Republic of Macedonia':'North Macedonia'}, inplace=True)

In [12]: # splitting the data into trafic air pollutants only

In [13]: traffic_apc = apc[apc['AirQualityStationType']=='Traffic']

In [25]: traffic_apc
Out[25]:
```

	Country	AQStationName	AirPollutionLevel	AirQualityStationType	AirQualityStationArea
4	Turkey	KAYSERI-HURRIYET	189	Traffic	urban
6	North Macedonia	Tetovo	178	Traffic	urban
8	North Macedonia	Rektorat	168	Traffic	urban
9	Turkey	CORUM-BAHABEY	165	Traffic	urban
15	North Macedonia	Centar	151	Traffic	urban

Figure 4.3. Data Tidying, dropping of unnecessary columns and up-to-date modifications [Stojchevski]

The dataset shown in Figure 4.4 was taken from the EEA official website for air pollutant emissions from the year 1990–2017. However, the data was standardized and broken up into respective parts previously in Excel, then fitted in the research with only the main pollutant components from the road transport, such as emissions of nitrogen oxides (NO_x) and Sulphur oxides (SO_x), carbon monoxide (CO) emissions and ammonia (NH_3) and as well as fine particulate matters $PM_{2.5}$ and PM_{10}.

```
In [5]: #read the data

In [6]: df = pd.read_excel('main_pollutant_components_EU33.xlsx')
        df.head(3) #checking the head of the data
Out[6]:
```

	Pollutant	NOx	NMVOC	NH3	PM2.5	SOx	CO	PM10
0	1990	7,534.449	5,670.114	14.035	348.126	605.332	35,215.063	400.753
1	1991	7,463.680	5,357.013	16.849	351.889	570.100	34,284.853	405.316
2	1992	7,553.961	5,272.586	24.794	353.764	591.911	33,536.874	408.446

```
In [6]: #set Pollutans as index column

In [8]: df.set_index('Pollutant', inplace=True)
        df.head(3) #checking the head of the data
Out[8]:
```

Pollutant	NOx	NMVOC	NH3	PM2.5	SOx	CO	PM10
1990	7,534.449	5,670.114	14.035	348.126	605.332	35,215.063	400.753
1991	7,463.680	5,357.013	16.849	351.889	570.100	34,284.853	405.316
1992	7,553.961	5,272.586	24.794	353.764	591.911	33,536.874	408.446

Figure 4.4. Data reading and indexing [Stojchevski]

chnaging the index type from object to datetime index and replace the commas into empty space in order to carry out an analysis and forecast

```
In [9]: df.index = pd.to_datetime(df.index, format='%Y')
        df.replace(",", "", regex=True, inplace= True)
```

```
In [10]: df.head()
```

Out[10]:

Pollutant	NOx	NMVOC	NH3	PM2.5	SOx	CO	PM10
1990-01-01	7534.449	5670.114	14.035	348.126	605.332	35215.063	400.753
1991-01-01	7463.680	5357.013	16.849	351.889	570.100	34284.853	405.316
1992-01-01	7553.961	5272.586	24.794	353.764	591.911	33536.874	408.446
1993-01-01	7313.359	4983.025	34.758	354.152	579.510	31972.690	408.856
1994-01-01	7028.582	4632.012	45.583	347.032	545.769	29339.783	403.605

Figure 4.5 Checking the index type from objects to datetime index and as well as replacing the commas into empty spaces [Stojchevski]

This dataset will provide with emission trends from 1990 until 2017 for the road transport and will carry out an analysis to show the rate of emissions of particulate matter, and several heavy metals and persistent organic pollutants. It will show the reduction rate on some of the main pollutant such as CO and NO_x as well as if there is some slight increase in 2017 compared to the previous year. In recent years, the rate of emission reductions has stagnated for many pollutants. And as noted, for a number, it has slightly increased and has tendencies to increase in the future as well. To check out those tendencies, I will use some forecasting models and specific forecasting tools such as ARMA and ARIMA, build from statsmodels library in Python. In statistics, and in particular in time series analysis, an autoregressive integrated moving average (ARIMA) model is a generalization of an autoregressive moving average (ARMA) model. Both of these models are fitted to time series data either to better understand the data or to predict future points in the series such as forecasting. ARIMA models are applied in some cases where data shows evidence of non-stationarity. To determine if the data is stationary or non-stationary, I will perform a so-called Dickey-Fuller test.

```
In [19]: # Load specific forecasting tools
         from statsmodels.tsa.arima_model import ARMA,ARMAResults,ARIMA,ARIMAResults
         from statsmodels.graphics.tsaplots import plot_acf,plot_pacf # for determining (p,q) orders
         from pmdarima import auto_arima # for determining ARIMA orders
```

```
In [20]: # Ignore harmless warnings
         import warnings
         warnings.filterwarnings("ignore")
```

Dickey-Fuller Test. I'll be using it a lot to determine if an incoming time series is stationary or not.

```
In [21]: from statsmodels.tsa.stattools import adfuller

         def adf_test(series,title=''):
             """
             Pass in a time series and an optional title, returns an ADF report
             """
             print(f'Augmented Dickey-Fuller Test: {title}')
             result = adfuller(series.dropna(),autolag='AIC') # .dropna() handles differenced data

             labels = ['ADF test statistic','p-value','# lags used','# observations']
             out = pd.Series(result[0:4],index=labels)

             for key,val in result[4].items():
                 out[f'critical value ({key})']=val

             print(out.to_string())          # .to_string() removes the line "dtype: float64"

             if result[1] <= 0.05:
                 print("Strong evidence against the null hypothesis")
                 print("Reject the null hypothesis")
                 print("Data has no unit root and is stationary")
             else:
                 print("Weak evidence against the null hypothesis")
                 print("Fail to reject the null hypothesis")
                 print("Data has a unit root and is non-stationary")
```

Figure 4.6. Performing Dickey-Fuller test to see if the incoming time series are stationary or non-stationary [Stojchevski]

```
In [22]: print('NOx')
         adf_test(df['NOx'])
         print('NMVOC')
         adf_test(df['NMVOC'])
         print('NH3')
         adf_test(df['NH3'])
         print('PM2.5')
         adf_test(df['PM2.5'])
         print('SOx')
         adf_test(df['SOx'])
         print('CO')
         adf_test(df['CO'])
         print('PM10')
         adf_test(df['PM10'])
```

Figure 4.7. Printing the Dickey-Fuller function [Stojchevski]

As a result of the Dickey-Fuller function, the following results were determined. It is shown that all of the mentioned pollutants from the dataset are non-stationary except the non-methane volatile organic compounds (NMVOCs) and that is mostly because there was not a specific trend over the past years for this pollutant.

```
NOx
Augmented Dickey-Fuller Test:
ADF test statistic       -0.420150
p-value                   0.906680
# lags used               0.000000
# observations           27.000000
critical value (1%)      -3.699608
critical value (5%)      -2.976430
critical value (10%)     -2.627601
Weak evidence against the null hypothesis
Fail to reject the null hypothesis
Data has a unit root and is non-stationary
NMVOC
Augmented Dickey-Fuller Test:
ADF test statistic       -4.736983
p-value                   0.000072
# lags used               9.000000
# observations           18.000000
critical value (1%)      -3.859073
critical value (5%)      -3.042046
critical value (10%)     -2.660906
Strong evidence against the null hypothesis
Reject the null hypothesis
Data has no unit root and is stationary
NH3
Augmented Dickey-Fuller Test:
ADF test statistic       -2.567615
p-value                   0.099877
# lags used               2.000000
# observations           25.000000
critical value (1%)      -3.723863
critical value (5%)      -2.986489
critical value (10%)     -2.632800
Weak evidence against the null hypothesis
Fail to reject the null hypothesis
Data has a unit root and is non-stationary
```

```
PM2.5
Augmented Dickey-Fuller Test:
ADF test statistic        2.188967
p-value                   0.998873
# lags used               0.000000
# observations           27.000000
critical value (1%)      -3.699608
critical value (5%)      -2.976430
critical value (10%)     -2.627601
Weak evidence against the null hypothesis
Fail to reject the null hypothesis
Data has a unit root and is non-stationary
SOx
Augmented Dickey-Fuller Test:
ADF test statistic       -2.603273
p-value                   0.092323
# lags used               9.000000
# observations           18.000000
critical value (1%)      -3.859073
critical value (5%)      -3.042046
critical value (10%)     -2.660906
Weak evidence against the null hypothesis
Fail to reject the null hypothesis
Data has a unit root and is non-stationary
CO
Augmented Dickey-Fuller Test:
ADF test statistic       -0.860977
p-value                   0.800552
# lags used               8.000000
# observations           19.000000
critical value (1%)      -3.832603
critical value (5%)      -3.031227
critical value (10%)     -2.655520
Weak evidence against the null hypothesis
Fail to reject the null hypothesis
Data has a unit root and is non-stationary
```

```
PM10
Augmented Dickey-Fuller Test:
ADF test statistic        1.801590
p-value                   0.998352
# lags used               0.000000
# observations           27.000000
critical value (1%)      -3.699608
critical value (5%)      -2.976430
critical value (10%)     -2.627601
Weak evidence against the null hypothesis
Fail to reject the null hypothesis
Data has a unit root and is non-stationary
```

Figure 4.8. Results of the Dickey-Fuller function to determine which of the components is stationary or non-stationary [Stojchevski]

Now that we know our stationarity of the components of our dataset it is very important to differentiate the time series. The differencing of a time series is a method of transforming a non-stationary time series into a stationary one. This is an important step in preparing data to be used in an ARIMA model. However, there is a function (auto_arima) that does this differentiating for us and was thus used accordingly in these analyses for every pollutant from the dataset.

Out[17]:

ARIMA Model Results

Dep. Variable:	D2.y	**No. Observations:**	26
Model:	ARIMA(0, 2, 1)	**Log Likelihood**	-199.778
Method:	css-mle	**S.D. of innovations**	519.694
Date:	Wed, 02 Oct 2019	**AIC**	405.556
Time:	12:40:57	**BIC**	409.330
Sample:	2	**HQIC**	406.643

	coef	std err	z	P>|z|	[0.025	0.975]
const	45.8642	37.612	1.219	0.235	-27.855	119.583
ma.L1.D2.y	-0.6729	0.182	-3.695	0.001	-1.030	-0.316

Roots

	Real	Imaginary	Modulus	Frequency
MA.1	1.4862	+0.0000j	1.4862	0.0000

This suggests that we should fit an ARIMA(0,2,1) model to best forecast future values of the series.

Figure 4.9. Auto ARIMA function for determining which of the model will fit the best for the forecast. In this case for the CO values it suggests that it should be fit an ARIMA (0,2,1) model to best forecast future values of the series. [Stojchevski]

The auto ARIMA function is differencing the model if in case of its non-stationarity and as well as giving the right ARMA or ARIMA model to best forecast future values of the series.

In addition, before we fit the prediction model it needs to determine the ρ, d and q values as well for the ARIMA or ARMA model. A non-seasonal ARIMA model is classified as an "ARIMA (p, d, q)" model, where p is the number of autoregressive terms, d is the number of non-seasonal differences needed for stationarity, and q is the number of lagged forecast errors in the prediction equation. However, with `pmdarima.auto_arima` stepwise function we can determine the ρ, d and q values and the algorithm will tell us if we should use the already used *p* and q terms the same and confirm if the already suggested ARIMA (0,2,1) still makes sense.

Let's take a look at pmdarima.auto_arima done stepwise to see if having p and q terms the same still makes sense:

```
In [164]: # auto arima stepwise for CO
stepwise_fit = auto_arima(df['CO'], start_p=0, start_q=0,
                          max_p=2, max_q=2,
                          seasonal=False,
                          d=None, trace=True,
                          error_action='ignore',    # we don't want to know if an order does not work
                          suppress_warnings=True,  # we don't want convergence warnings
                          stepwise=True)           # set to stepwise

stepwise_fit.summary()

Fit ARIMA: order=(0, 2, 0); AIC=411.865, BIC=414.381, Fit time=0.004 seconds
Fit ARIMA: order=(1, 2, 0); AIC=410.078, BIC=413.852, Fit time=0.054 seconds
Fit ARIMA: order=(0, 2, 1); AIC=405.556, BIC=409.330, Fit time=0.064 seconds
Fit ARIMA: order=(1, 2, 1); AIC=407.489, BIC=412.521, Fit time=0.133 seconds
Fit ARIMA: order=(0, 2, 2); AIC=nan, BIC=nan, Fit time=nan seconds
Fit ARIMA: order=(1, 2, 2); AIC=nan, BIC=nan, Fit time=nan seconds
Total fit time: 0.279 seconds
```

Out[164]: ARIMA Model Results

Dep. Variable:	D2.y	**No. Observations:**	26
Model:	ARIMA(0, 2, 1)	**Log Likelihood**	-199.778
Method:	css-mle	**S.D. of innovations**	519.694
Date:	Tue, 01 Oct 2019	**AIC**	405.556
Time:	13:31:57	**BIC**	409.330
Sample:	2	**HQIC**	406.643

	coef	std err	z	P>|z|	[0.025	0.975]
const	45.8642	37.612	1.219	0.235	-27.855	119.583
ma.L1.D2.y	-0.6729	0.182	-3.695	0.001	-1.030	-0.316

Roots

	Real	Imaginary	Modulus	Frequency
MA.1	1.4862	+0.0000j	1.4862	0.0000

Figure 4.10. `pmdarima.auto_arima` *stepwise function to check [Stojchevski]*

The figure 4.10 shows the example of auto ARIMA stepwise performed on CO pollutant from the dataset and the algorithm suggested and confirmed that the best fitting forecasting model for that specific pollutant should be ARIMA (0, 2, 1). For the other pollutants, the same auto ARIMA stepwise function is performed accordingly.

Furthermore, in order to get the predictions and evaluations of the model accurately, it needs to split the data into train/test sets. The training set is used to train the model, and the validation/test set is used to validate it on data it has never seen before. The classic approach is to do a simple 80%-20% split.

Now let's train & test the ARIMA model for CO and other components, evaluate it, then produce a forecast of future values. Split the data into train/test sets

In [31]:
```
len(df)
```
Out[31]: 28

In [27]:
```
# Set years for testing
train = df.iloc[:25]
test = df.iloc[24:]
```

Fit an ARIMA(0,2,1) Model

In [29]:
```
# CO
model = ARIMA(train['CO'],order=(0, 2, 1))
results = model.fit()
results.summary()
```

Out[29]:

ARIMA Model Results

Dep. Variable:	D2.CO	**No. Observations:**	23
Model:	ARIMA(0, 2, 1)	**Log Likelihood**	-178.031
Method:	css-mle	**S.D. of innovations**	548.758
Date:	Thu, 03 Oct 2019	**AIC**	362.061
Time:	15:32:41	**BIC**	365.468
Sample:	01-01-1992	**HQIC**	362.918
	- 01-01-2014		

	coef	std err	z	P>|z|	[0.025	0.975]
const	38.9959	41.425	0.941	0.357	-42.195	120.187
ma.L1.D2.CO	-0.6867	0.204	-3.373	0.003	-1.086	-0.288

Roots

	Real	Imaginary	Modulus	Frequency
MA.1	1.4563	+0.0000j	1.4563	0.0000

Figure 4.11. Splitting the data into train/test sets then fit the train data to ARIMA model [Stojchevski]

Next step before start of the retraining the model on the full data, and forecasting the future, it is needed to evaluate the model with determining the mean squared error (MSE) and Root Mean Square Error (RMSE) to see how accurate the model is and if there are major or minor errors performed in the predictions. The mean squared error (MSE) of an estimator measures the average of the squares of the errors is, the average squared difference between the estimated values and the actual value. The Root Mean Square Error (RMSE) is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how to spread out these residuals are. In other words, it tells us how concentrated the data is around the line of best fit.

Evaluate the Model

In [243]:
```
from sklearn.metrics import mean_squared_error

error = mean_squared_error(test['CO'], predictions)
print(f'ARIMA(0,2,1) MSE Error: {error:11.10}')
```
```
ARIMA(0,2,1) MSE Error: 27510.22766
```

In [244]:
```
from statsmodels.tools.eval_measures import rmse

error = rmse(test['CO'], predictions)
print(f'ARIMA(0,2,1) RMSE Error: {error:11.10}')
```
```
ARIMA(0,2,1) RMSE Error: 165.8620742
```

Figure 4.12. Evaluating the model with MSE and RMSE [Stojchevski]

In Figure 4.12 we can see that the MSE and RMSE errors make sense and the model performs good. Indeed, it is not the ideal fit of the predictions, but it is the best model that can be performed.

The final step is retraining the model on the full data and forecast in the future for each pollutant from the dataset. In this particular model, I forecasted the dataset for 4 years in advance. The forecast should not be bigger than the length of the time series of data to get more accurate results.

Retrain the model on the full data, and forecast the future¶

```
In [263]: model = ARIMA(df['CO'],order=(0,2,1))
          results = model.fit()
          fcast = results.predict(len(df),len(df)+4,typ='levels').rename('ARIMA(0,2,1) Forecast')

In [264]: model1 = ARIMA(df['NOx'],order=(0,1,1))
          results1 = model1.fit()
          fcast1 = results1.predict(len(df),len(df)+4,typ='levels').rename('ARIMA(0,1,1) Forecast')

In [265]: model2 = ARIMA(df['SOx'],order=(1,1,0))
          results2 = model2.fit()
          fcast2 = results2.predict(len(df),len(df)+4,typ='levels').rename('ARIMA(1,1,0) Forecast')

In [266]: model3 = ARIMA(df['PM10'],order=(0, 2, 1))
          results3 = model3.fit()
          fcast3 = results3.predict(len(df),len(df)+4,typ='levels').rename('ARIMA(0,2,1) Forecast')

In [267]: model4 = ARIMA(df['PM2.5'],order=(0, 2, 1))
          results4 = model4.fit()
          fcast4 = results4.predict(len(df),len(df)+4,typ='levels').rename('ARIMA(0,2,1) Forecast')

In [268]: model5 = ARMA(df['NH3'],order=(2, 1))
          results5 = model5.fit()
          fcast5 = results5.predict(len(df),len(df)+4).rename('ARMA(2,1) Forecast')

In [271]: #Plot predictions against known values
          title = 'Main Pollutants from transport'
          ylabel='Value'
          xlabel='Year'

          ax1 = df['CO'].plot(legend=True,figsize=(12,9),title=title, color='Blue')
          ax2 = df['NOx'].plot(legend=True,figsize=(12,9),title=title, color = 'Red')
          ax3 = df['SOx'].plot(legend=True,figsize=(12,9),title=title, color = 'lightgrey')
          ax4 = df['PM10'].plot(legend=True,figsize=(12,9),title=title, color = 'Black')
          ax5 = df['PM2.5'].plot(legend=True,figsize=(12,9),title=title, color = 'Green')
          ax5 = df['NH3'].plot(legend=True,figsize=(12,9),title=title, color = 'Purple')
          fcast.plot(legend=True, color='Blue')
          fcast1.plot(legend=True, color = 'Red')
          fcast2.plot(legend=True, color = 'lightgrey')
          fcast3.plot(legend=True, color = 'Black')
          fcast4.plot(legend=True, color = 'Green')
          fcast5.plot(legend=True, color = 'Purple')
          ax.autoscale(axis='x',tight=True)
          ax.set(xlabel=xlabel, ylabel=ylabel)
          ax4.grid(True)
```

Figure 4.13. Retraining the model and forecast in the next four years [Stojchevski]

Other similar analyses were performed on other datasets mentioned in the previous Chapter 4.3. The visualization of the data and the plots will be shown in the result chapter, where the progress of the emissions evaluated from the data and the various variants for dealing with air pollution from road transport and as well as other possibilities for the further emission reduction will be explained.

4.5. Barriers

There are certain variations in how the research design was initially intended and how it evolved during the ongoing research, which will be openly discussed in this chapter on research barriers. Firstly, it stretches from the point that the research paper was initially meant to be written in partnership with Škoda Auto a.s. and the department of Emission Measurement there, while I was doing an internship as a Data Analyst at Škoda. Other difficulties that I faced were finding the proper data for the aim of the thesis and selecting the parameters, to the selection of literature, due to the thesis general intention.

Firstly, starting with the barriers experienced within the Škoda Auto a.s. and the department of Emission Measurement. The preliminary goal was to get the data from this department based on the measuring data from the newly produced vehicles in Škoda and their driving cycles. The

initial aim of the thesis was to base the research and data evaluation primarily on Škoda and their emission values and measurements of newly produced cars in the European Union. Further, the focus was intended to be on the emission standards the brand has to follow regarding the new EU targets. However, while trying to obtain the data, the problem arose that most of the data needed were restricted and only accessible to internal employees. I was not granted access to any confidential measuring statistics.
Consequently, this focus of the research was being shifted and readjusted. The further data collection had to be done independently without further involvement with Škoda Auto but open and public data sources. Now the main data focus is rather on all car brands distributing cars in the EU, then a single one, which broadens the topic further and allows a more general analysis of the current status and further reduction of exhaust gases of combustion engines of several car brands.

Moreover, when it comes to finding the proper data, several obstacles were being faced. One of the main data problems that I confronted was the data publication. Most of the data that is being published is mostly publicized one year after the data is measured and therefore, the datasets are generally not up-to-date. Most of the data were updated and published from the period of 2018 and 2019, but the parameters and the measurements are covering datasets mostly for a period of 2017 and 2018. Other obstacles that were confronted regarding the data analysis for this research was the technical barriers that prevented efficiently working with datasets, due to the quality and the availability of the open data. Although many datasets have been made available in the past years, the availability of open data persists to be a barrier. The poor discoverability of the data is a barrier, which is also related to the low levels of quality in the descriptions of the data sets themselves and the plurality of platforms where the data can be found. When the descriptions are not specific enough or when the dataset is disseminated on a particular platform, it is hard for the user to find the needed data even when it is published. The quality of open data appears to be even more problematic, with data being published in different structures and in different formats, as well as lack of standardization in the metadata. When dispersed among platforms in different countries, also language barriers might play a role in the poor discoverability of Open Data. This is even more prominent when portals have only limited or very basic search functionalities.

As a next barrier, the selection of countries for the data analysis must be mentioned. Very often the desired focus on Europe as a whole and the inclusion of all states into the analysis could not be accomplished. The reason behind is that not all European states are following the same legislation from the EC. Certain non-European union member states do not follow these legislations and are not as strict as member states or cooperating states in emission controlling and reducing. This can lead to falsified results, because emission outputs can vary heavily between countries. As an example, most of the Balkan countries, such as North Macedonia, do not follow the EU legislation requirements that strictly as the EU member states. Vehicles driven there create much higher concentrations of pollution than cars driven within EU member states, for example Finland. In 2016 the highest daily mean concentration of PM_{10} output from traffic in North Macedonia was 135 $\mu g/m^3$, whereas in Finland the measured output was only 27 $\mu g/m^3$. A further problem is that in North Macedonia the number of cars being driven is a much smaller than in Finland. The data for PM_{10} concentration used for this analysis though is measured at station level with daily mean concentration for particulate matter < 10 µm (PM_{10}): not more than 35 days/year with a daily mean concentration exceeding 50 $\mu g/m^3$ and air pollution level corresponds to the 36th highest daily mean concentration.

In this context, this research includes estimates for all main pollutants from the road transport and combustion engines, all relevant source categories, all years and all territorial areas in Europe that the datasets were already provided. For instance, substances for the dataset for Air pollutant emissions data (Gothenburg Protocol, LRTAP Convention), which there are current reporting obligations in the LRTAP Convention and the Gothenburg Protocol, as already specified. One Member State (Greece) did not submit any data. Three Member States (Luxembourg, Malta and Romania) did not provide a complete time series. Austria and Luxembourg submitted no data for additional HMs, and Finland and Poland no data for Selenium (Se). Austria, Finland and Spain have submitted only total Polycyclic aromatic hydrocarbon (PAHs). Therefore, it was not possible to stay consistent with the selection of countries and pollutants used in the analysis.

Chapter 5

5. Current emission state from road transport and progress towards the better air quality in Europe

The previous chapters have seen the methodological explanation of how the analysed data was approached in order to get results. The results will be shown in this chapter, which firstly will elaborate on the analyses and visualizations of the collected data and afterwards analyse possible variants for further emission reduction. Better technologies will be discussed and outlined. However, the recent state of emission control technology from combustion engines in the EU, mentioned in Chapter 3.5, cannot significantly reach the current and the future targets that the European Commission is proposing. As a result, a shift to electro-mobility or other alternatives is needed such as hybrid engines, alternative fuels.
Before going into detail, it is important to indicate that the road transport, which is almost entirely based on fossil energy, is the second biggest source of greenhouse gas (GHG) emissions in the EU. It contributes to approximately one quarter of the total EU GHG emissions (EC, 2014). The largest share of EU GHG pollution from road transport is caused by passenger cars. Despite significant improvements in the fuel efficiency of passenger cars over the last decades (discussed in Section 3.5), this is counteracted by more powerful engines, bigger vehicle sizes like SUV’s and an increasing number of the kilometres driven by vehicles.

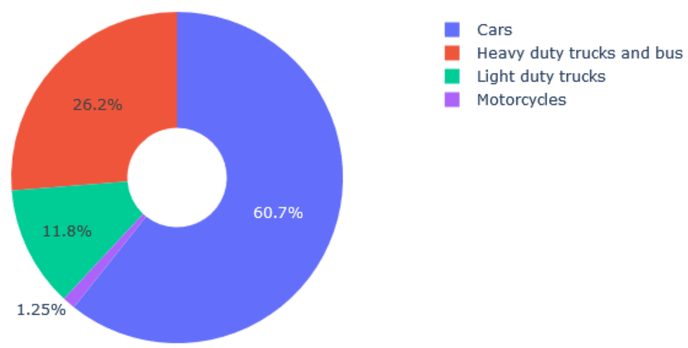


Figure 5.1. Share of road transport GHG emissions. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are analysed in this indicator. [Stojchevski, 2019] [Data source: Section 4.3, Data: a)]

GHG emissions from the EU-28 transport sector have been rising since 2014 (including international aviation but excluding international shipping). Compared to 2015, emissions increased by nearly 3 per cent in 2016, primarily due to higher road transport emissions, followed by aviation. Transport (including aviation and shipping) accounted for 27% of overall greenhouse gases in 2016. EEA estimates show that in 2017 transport emissions (including aviation) continued to rise by 1.5% [74]

In 2016, road transport was responsible for almost 72 % of total greenhouse gas emissions from transport (including international aviation and international shipping). If we exclude international aviation and international shipping, 60,7 % of these emissions were contributed by passenger cars, while 26,2 % came from heavy-duty vehicles.

Due to a significant rise in passenger-kilometre and tone-kilometre demand, GHG emissions from road transport (excluding international aviation and excluding international shipping) have drastically increased and were still more than 20 % above levels from 1990 in 2016.

However, the increase in transport GHG emissions is below the expected target path until 2016. This increase occurs despite improvements in the efficiency of transport vehicles and is broadly in line with increases in the level of economic activity - as measured by gross domestic product (GDP) - as well as increases in demand for both passenger and freight transport. The transport sector remains the only main European economic sector in which GHG emissions have increased, when compared with the 1990 levels.

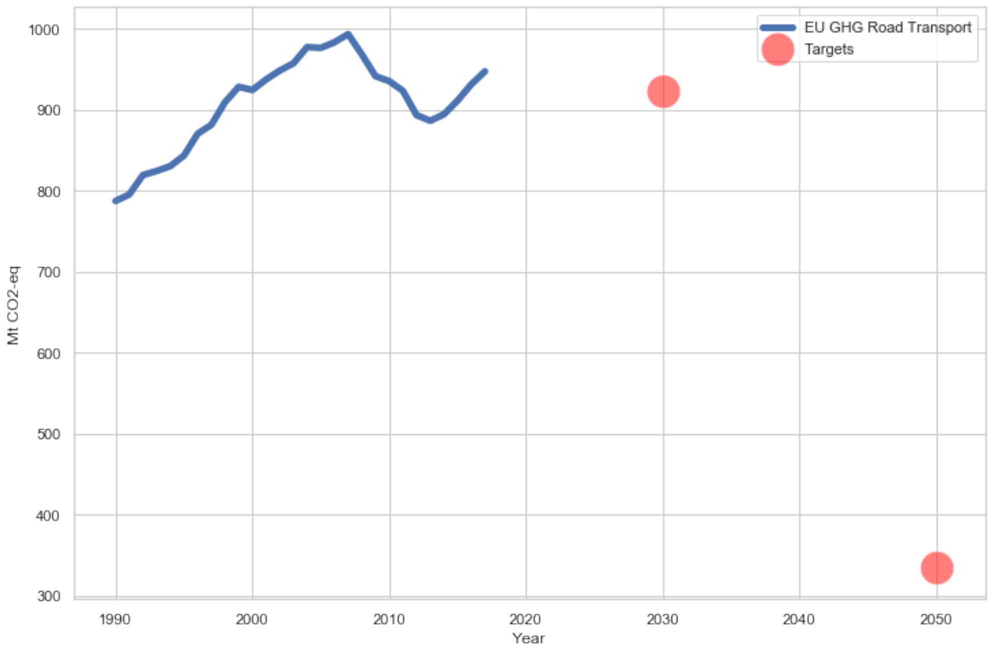


Figure 5.2 Total EU GHG emission from road transport from 1990 -2017 (aviation and maritime are not included in the analysis). [Stojchevski, 2019] [Data source: Section 4.3, Data: a)]
**red dots are indicating 2030 and 2050 targets set by EC*

The global warming potential values used in this measure are those taken from IPCC for the pre-2015 period and those taken from IPCC for the post-2015 period, in accordance with the rules of the United Nations Framework on Climate Change (UNFCCC). The data is weighted to give the total CO_2 emissions in millions of tons equivalent (Mt CO_2eq) to the following global warming potentials for each greenhouse gas:

- Pre-2015: CO_2 = 1, CH_4 = 21, N_2O= 310;
- Post-2015: CO_2 = 1, CH_4= 25, N_2O = 298.

However, there are several European policies and strategies that aim to reduce greenhouse gas emissions from transport. The EU's overall goal, set in the 2011 “White Paper for Transport”, wants to reduce greenhouse gas emissions from transport (including international aviation but excluding international shipping) by 2050 to a level that is 60 % below the level of 1990. This includes the intermediate goal for 2030 of reducing greenhouse gas emissions from transport by 20 % compared to 2008 levels. It is equivalent to an +8 % increase compared to 1990 levels. These overall transport targets are monitored annually and are in line with the economy-wide targets of a 20 % reduction in total greenhouse gas emissions by 2020 towards 1990 levels and a 40 % reduction by 2030. Other transport policies that support the achievement of these targets, such as the various regulations that set CO_2 emission targets for new passenger cars and vans, are also monitored in the Transport and Environment Reporting Mechanism (TERM) [79]. Moreover, specific targets, relevant to the performance of the transport sector on climate, are presented in the following pieces of EU legislation:

- the Renewable Energy Directive (2009/28/EC), which sets a 10 % share of renewable energy in the transport sector’s final energy consumption for each Member State by 2020; [79]
- the Regulations on CO_2 emissions from new passenger cars (443/2009) and new light commercial vehicles (510/2011) setting average emission limits of 95 g CO_2/km by 2021 (new cars) and 147 g CO_2/km by 2020 (new vans). [79]

In addition, the Fuel Quality Directive (98/70/EC) sets out reporting requirements relating to the quality of petrol and diesel fuels sold for road transport in their territories. Member States shall require suppliers to gradually reduce the life cycle GHG emissions per unit of energy from fuel and energy supplied by up to 10 % by 31st December 2020.

It is the responsibility of Member States to reduce transport emissions through national policies in order to reach their national Effort Sharing targets (which cover sectors such as transport, buildings, agriculture, waste, etc.). These Effort Sharing targets are equivalent to a 10 % reduction compared with 2005 levels by 2020, and a 30 % reduction by 2030. In Figure 5.3 is shown which state member has the highest percentage of total GHG emission and effort each EU member state is contributing to better air quality from transport. Turkey by far is the highest polluter of total GHG from transport out of EU-30 member states (3 EU members are not included in the analyses due to luck of applied data in the data set).[80]

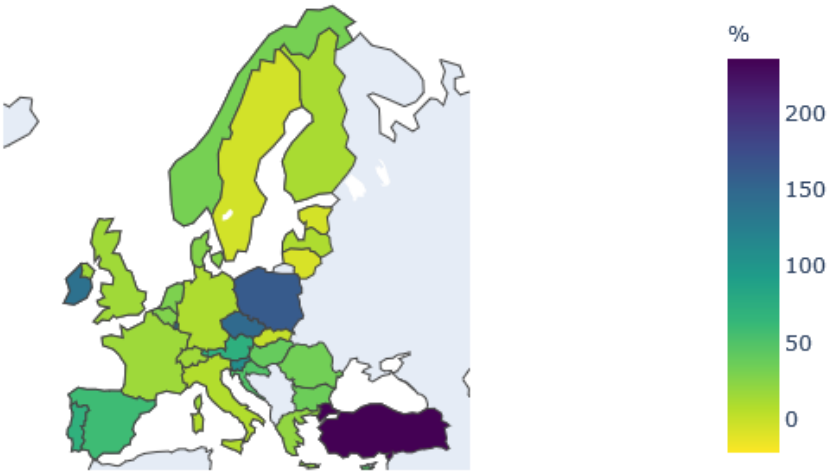


Figure 5.3. Change in total GHG emissions from transport in EU (%) (aviation and maritime are included in this analyses) [Stojchevski] [Data source: Section 4.3, Data: a)]

5.1 Trends, targets and forecast of EU-28 main pollutant emissions from road transport

The following sections summaries the contributions each Member State has made to the total EU-28 emissions from road transport of NO_x, SO_x, NH_3, CO, $PM_{2.5}$, PM_{10}. The data was taken from the EEA official website and fitted in the research with only the main pollutant components from the road transport, such as emissions of nitrogen oxides (NO_x) and sulphur oxides (SO_x), carbon monoxide (CO) emissions and ammonia (NH_3) as well as fine particulate matters $PM_{2.5}$ and PM_{10}. Data for several countries (at least for some years) were missing and could not be gap-filled. Therefore, the EU total is incomplete, which means that the report includes estimates for all main pollutants from the road transport and territorial areas of only 28 EU member countries that have submitted their data between 1990-2017. [75]

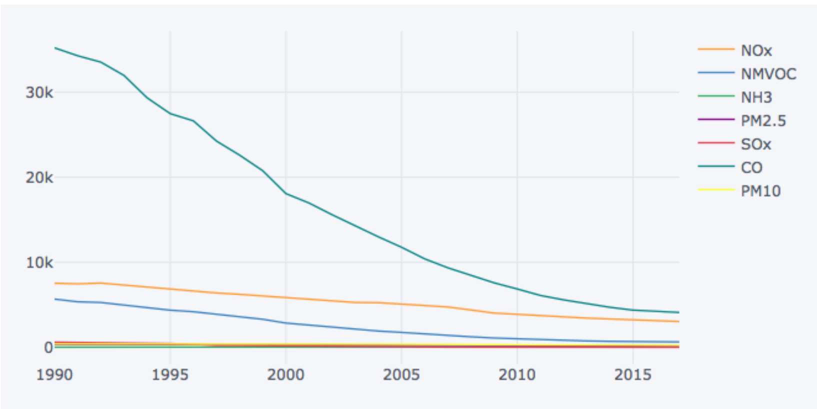


Figure 5.4. Trend of main pollutant components from the road transport [Stojchevski 2019] [Data source: Section 4.3, Data: a)]

5.1.1 Emission from the main pollutants of road transport and progress towards the better air quality in Europe

The Convention on Long-range Transboundary Air Pollution (LRTAP) data describes and tracks the emissions of key air pollutants over the past years. It is submitted by the EU to the

UNECE under the requirements of the Gothenburg Protocol to the LRTAP Convention, which aims to limit and gradually reduce and prevent air pollution. The Gothenburg Protocol specifies emission ceilings for the pollutant's NO_x, NMVOCs, SO_x and NH_3. Parties to the protocol must meet the targets until 2020 and thereafter. [75]

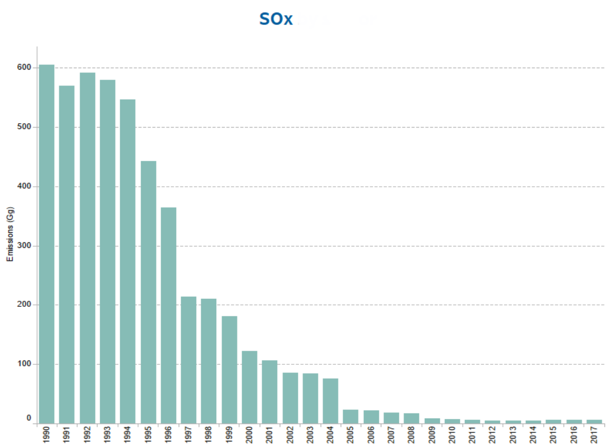
This indicator analyses emissions from road transport of CO, NO_x, NMVOCs, PM_{10}, $PM_{2.5}$ and SO_x over a certain time period. These pollutants can be grouped into acidifying substances, particulate matters and ozone precursors. Transport contributes significantly to emissions of NO_x, NMVOCs, PM and CO. NO_x contributes to acidification, the formation of ground-level ozone and particulate formation.

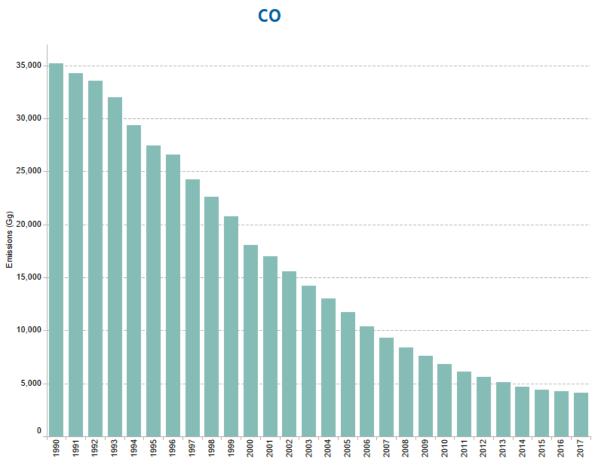
- Acidifying substances: the acidification of soils and waters is caused by emissions of NO_x, SO_x and NH_3 into the atmosphere, and their subsequent chemical reactions and depositions in ecosystems and on materials. The deposition of acidifying substances causes damage to ecosystems, buildings and other materials (corrosion).

- Particulate formation: airborne PM has adverse effects on human health and can be responsible for and/or contribute to a number of respiratory problems. In this assessment, 'particulate formation' refers to primary emissions of PM_{10} and $PM_{2.5}$ and emissions of precursors (NO_x, SO_x and NH_3), which lead to the secondary physio-chemical production of inorganic PM in the atmosphere. A large fraction of the urban population is exposed to levels of fine PM in excess of air quality limit values set for the protection of human health.

- Ozone precursors: emissions of NMVOCs, NO_x, CO and methane (CH_4) contribute to the formation of ground-level (tropospheric) ozone, which has severe effects on human health and ecosystems.

In 2017, emissions of all pollutants from the road transport were lower than in 1990. Among the main air pollutants, the largest reductions across the EU (in percentage terms) since 1990 were for SO_x emissions, which decreased by 91 %, followed by CO (-69 %), NMVOCS (-61 %), NO_x (-58 %), and NH_3 (-24 %). Also, $PM_{2.5}$ and PM_{10} emissions have both decreased by 26 % since 2000. [81]





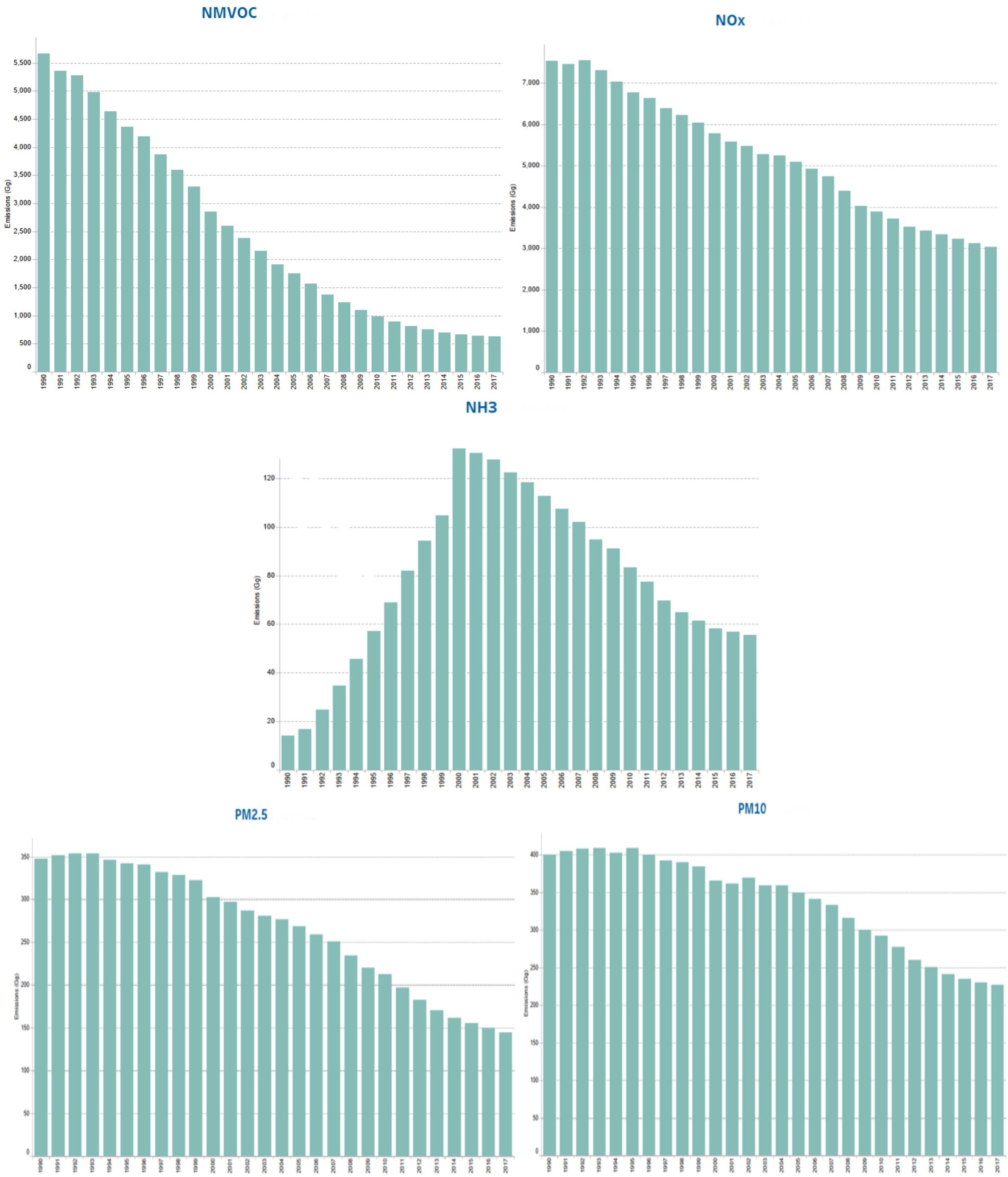


Figure 5.5. Changes of main emissions from road transport [(Gothenburg Protocol, LRTAP Convention) 1990-2017]

The relative changes in emissions of pollutants from the transport sector are shown in the above figures. Emissions from road transport have declined since 1990, despite the general increase in activity within the sector. Emission reductions from the road transport sector are primarily a result of fitting catalytic converters to vehicles and recent emissions control technology for the combustion engines (see Chapter 3.5). The legislative standards have driven this move. Nevertheless, the road transport sector represents the largest source of NO_x emissions, accounting for 39 % of total EU emissions in 2017. A recent study estimated that excess diesel vehicle NO_X emissions in 2015 were linked to ~38,000 premature deaths worldwide, with the EU having a higher number of deaths compared to other regions. In fact, if diesel vehicle NO_X

emissions were within EU certification limits, the mortality burden in Europe would drop by 10% each year [82]. NO_x reacts with atmospheric chemicals to form $PM_{2.5}$. Exposure to $PM_{2.5}$ can cause stroke, ischemic heart disease, chronic obstructive pulmonary disease, lung cancer, and lower respiratory infections. $PM_{2.5}$ caused 4.2 million premature deaths worldwide in 2015. When combined with volatile organic compounds and sunlight, NO_x helps form ground-level ozone, a major component of smog. Ozone can cause or exacerbate chronic lung diseases like asthma, chronic obstructive pulmonary disease, or emphysema, especially among vulnerable populations like children and the elderly, for whom it may prove deadly. Researchers attribute 254,000 premature deaths to ozone pollution in 2015. NO_x emissions also affect ecosystems and agricultural crops. Ozone pollution is toxic to plants and contributes to loss of biomass, crop yields, and forest productivity. $PM_{2.5}$ pollution reduces solar irradiation, decreases photosynthesis in plants and reduces their biomass [83]. The loss in biomass means less carbon is sequestered in plants, leaving more CO_2 in the atmosphere. Both ozone and $PM_{2.5}$ pollution can directly change the way ecosystems work by affecting the exchange of CO_2 and water vapor across the surface of leaves, which can have significant effects on hydrology and even changing stream flows [84]. However, regarding to road transport, EU governments and car manufacturers continue to make a significant contribution to reduce emissions of NO_X (48% since 1990), that is due to emission control technologies and after-treatments from the Diesel-powered vehicles (see Chapter 3.5) [85]. Nevertheless, the contribution of road transport to harmful NO_2 concentrations, especially in urban areas, is considerably higher, because emissions occur close to the ground and mainly in densely populated areas.

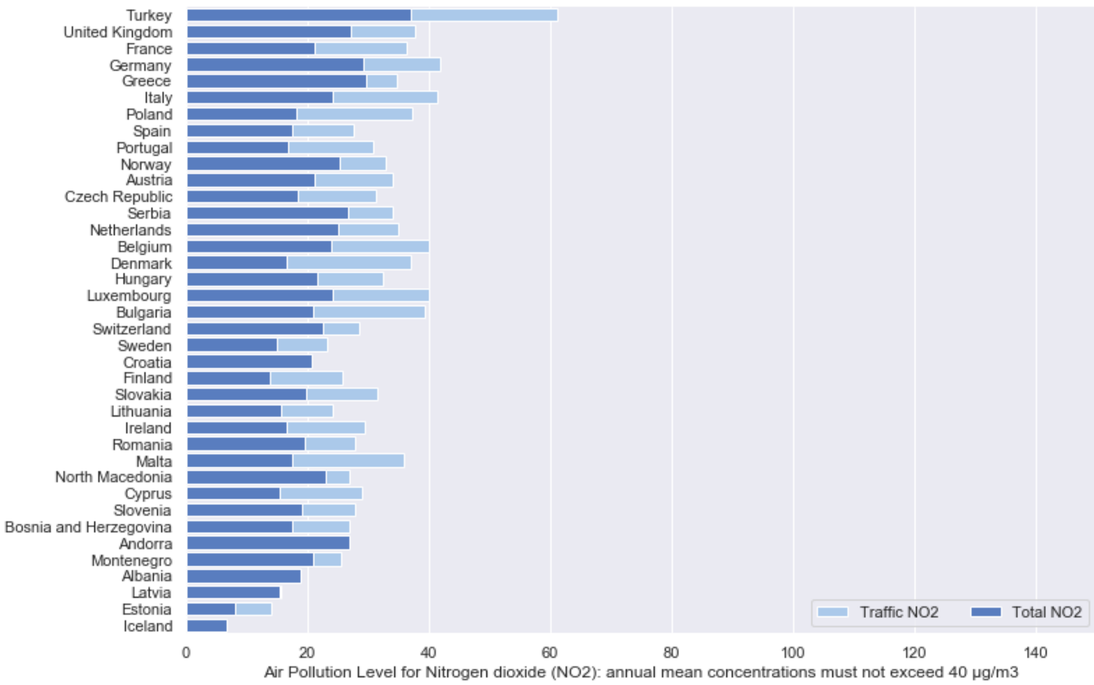


Figure 5.6. Total NO_2 concentration comparing with NO_2 from traffic [Stojchevski]

Figure 5.6 is showing European countries with the biggest pollution of total NO_2 concentration comparing with NO_2 from traffic in 2017. It clearly shows that Turkey is the biggest polluter in Europe for NO_2 and that is mostly because of the burning of fossil fuels. According to the Turkish Ministry of Energy and Natural Resources there are currently six old coal plants in Turkey and the government has already started the conversion of the chimneys of these old plants with latest technology [86]. However, when it comes to the concentration of NO_2 from traffic, despite improvements in vehicle emission control technology, the rapid growth of vehicle ownership and average trip length during the past decades has created an unhealthy air quality in urbanized areas, whose contribution is around half of the total concentration of NO_2. The quality of the air we breathe is even more important for mega cities like Istanbul, having the busiest traffic flow and highest population in Turkey.

When it comes to PM_{10} concertation in Europe the highest PM_{10} concentration from traffic sector are measured in North Macedonia, which is corresponding to the total amount of PM_{10} particles in this region. This means, that almost all of the PM_{10} concentration are coming from the traffic sector.

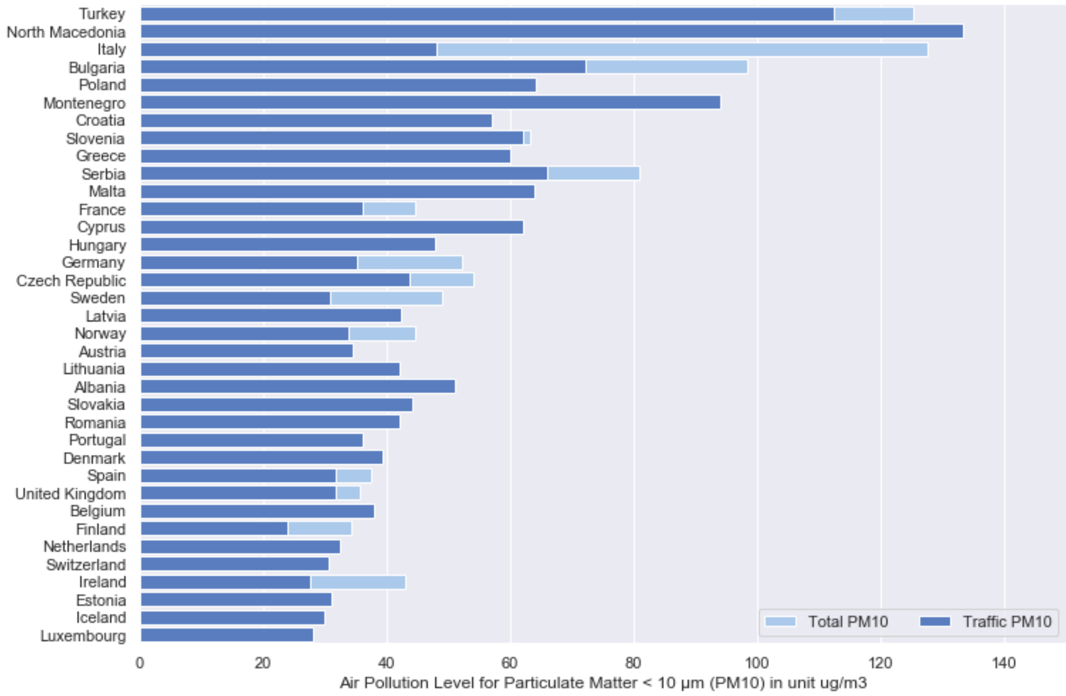


Figure 5.7. Total PM_{10}concentration comparing with PM_{10} from traffic [Stojchevski] [Data source: Section 4.3, Data: b)]

Air pollution causes more than 1,300 premature deaths per year in the Macedonian capital, Skopje according to official statistics. Particle pollution (PM) in Skopje is more than ten times higher than the air quality standards set by the European Union - both regarding PM_{10} and $PM_{2.5}$. Skopje's public transportation system is underdeveloped, consisting only of buses. Automobiles and public transport vehicles are mostly old, and the regulation of the newest Euro Standards don't have strict implementation in North Macedonia and its capital, as well as the other city in this country. Many of these do not meet the most basic environmental standards. Bicycles are rarely used because the city lacks the necessary infrastructure and road traffic culture makes cycling risky. For instance, Stuttgart, one of the most polluted cities in Germany, raises an alarm when the PM_{10} particles in the air reach 80 micrograms per cubic meter. In Skopje, the average for winter months is more than twice as high - around 200 - with peaks often reaching 600 micrograms of PM_{10} or more. [87]

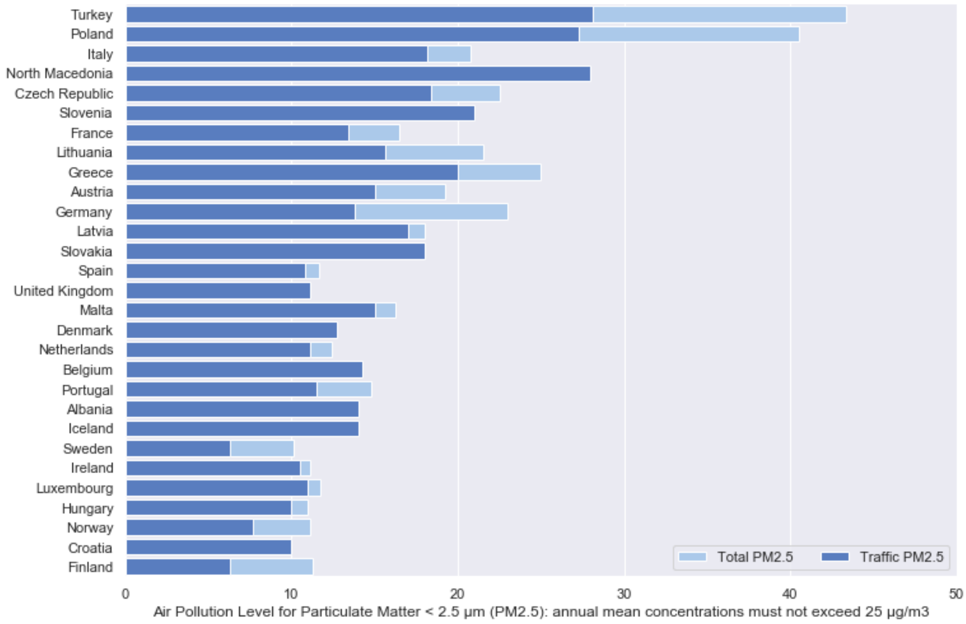


Figure 5.8. Total $PM_{2.5}$concentration comparing with $PM_{2.5}$ from traffic [Stojchevski] [Data source: Section 4.3, Data: b)]

The scale of policy actions undertaken in Europe to specifically address transport-related air pollution has increased over recent years, reflecting the important contribution that transport still makes in relation to poor air quality. Local and regional air quality management plans - including initiatives such as low-emission zones in cities or congestion charges are now undertaken in many areas where air pollution from transport is high. Different European legal mechanisms are used to address air quality. These include the setting of limits or target values for ambient concentrations of pollutants, limits on total emissions (e.g. national totals) and regulating emissions from the traffic sector either by setting emission standards (like EURO 6) or by setting requirements for fuel quality.

Although, both the NECD and the Gothenburg Protocol set reduction targets for SO_2, NO_x, NMVOCs and NH_3 for the EEA-33 member countries there are substantial differences in emission ceilings due to different sensitivities of the ecosystems affected and the technical feasibility of making reductions. Most of the less developed European countries or non-EU member states are having bigger difficulties to follow these policies and legislations. This is mostly because of the judicial system and because the passage towards renewable energies in these countries is very slow or they suffer from significant levels of energy poverty and rely on very unmodern polluting plants and outdated control technologies. For instance, the Western Balkan states (Albania, Bosnia-Herzegovina, Serbia, Kosovo, North Macedonia, and Montenegro) stand among the European leaders in fossil fuel air pollution. 16 coal power plants in the western Balkans cause as much pollution as all 250 plants active within the European Union. [88]

It must be mentioned, that the reduction of emissions in Europe varies from state to state and within each state's regions [75]. Therefore, a consistent and overall implementation of emission targets and regulations cannot be put into action at ease.

5.1.2. Forecast of the main pollutant from the road transport

Road transport remains very dependent on fossil fuels, with oil-derived fuels accounting for 95 % of final energy consumption in transport. After reaching its peak in 2007, road transport GHG in EU decreased continuously until 2013, when it reached 11 % below 2007 levels. This was due to improvements in energy efficiency, the impacts of the economic recession that caused a subsequent decline in transport demand, and a period of high oil prices after 2010. Since 2014, GHG from road transport in EU has been following an upward trend at an average rate of 1.7 % each year [89].

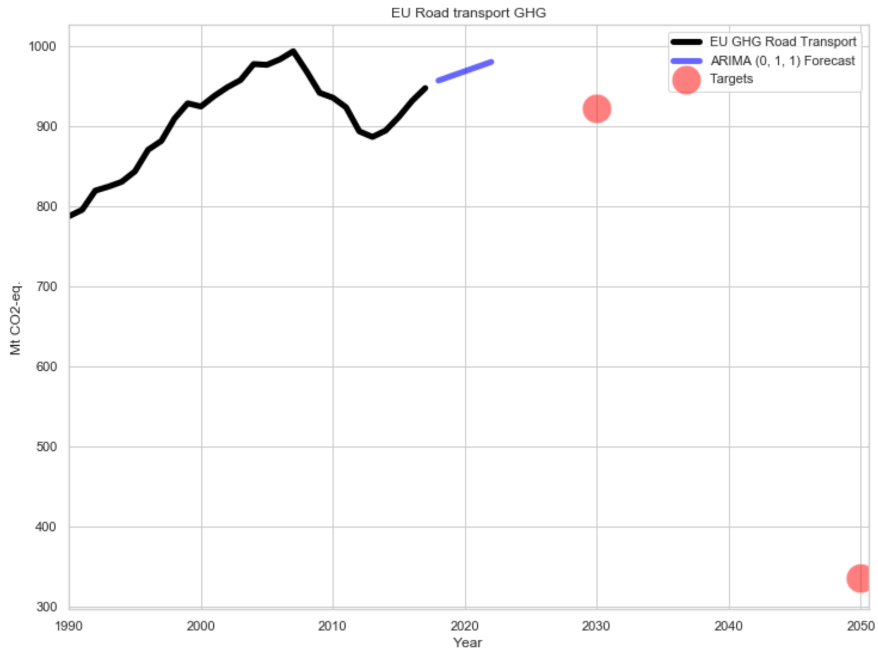


Figure 5.9. Forecast and prediction of the following upward trend of EU GHG (aviation and maritime are not included in the analyses) [Stojchevski] [Data source: Section 4.3, Data: a)]

The latest data available on past trends show that the EU transport sector is currently not on track to reach the policy targets on total GHG emissions in the last four years. As this ARIMA (0, 1, 1) forecast shows, if this upward trend from the road transport is following this progress and not any additional implementation are made, the target path that EC announced will be very hard to reach.

In order to reach a 70 % reduction in oil consumption from road transport compared with 2008 the additional efforts needed remain challenging. Even though the EU was on the target path until 2014, it exceeded the projected downward target trend in 2015 and 2016, due to an increase in energy consumption in road transport. Transport oil consumption will need to fall by more than two-thirds to meet the objectives of a 70 % reduction of oil consumption by 2050 [89].

When comes to the emissions of the main pollutants from the road transport the trend here is decreasing and mostly of the emissions were significantly lower than in 1990, except NH_3 (but significantly decreased after 2000). Among the main air pollutants, the largest reductions across the EU since 1990 were for SO_x emissions, followed by CO, NMVOCS, NO_x, $PM_{2.5}$, PM_{10} and NH_3.

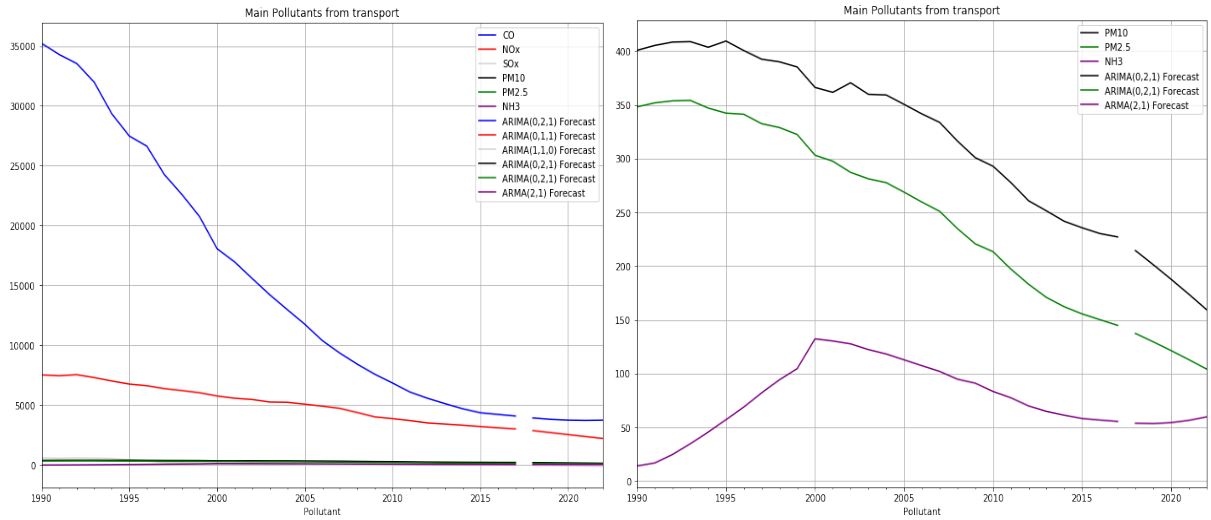


Figure 5.10. Main pollutant forecast of main Pollutants from Road Transport and enlarged plot with only PM_{10}, $PM_{2.5}$ and NH_3 pollutant forecast, [Gg (1000 tonnes) [Stojchevski] [Data source: Section 4.3, Data: b)]

Although, the recent emission after-treatment and emission control technology such as the three-way catalyst, invented in the 1970s, is inexpensive and causes little or no penalty to fuel economy, performance, drivability, or maintenance. And as well it is very effective, for instance a new 2017 gasoline-engine passenger car, properly tuned and operating in normal conditions, has only a negligible amount of NO_x present in the exhaust as it exits the tailpipe. However, this does not mean that the NO_x or other pollutant problem is fully solved for gasoline engines; a hundred thousand cars stuck in traffic still add up to a health hazard and a pollution problem, as show in the Figure *5.10*. Even though most of the main emissions from road transport have declined since 1990, there is a general increase in activity within the whole sector of the road transport sector and represents the largest source of NO_x emissions, accounting for 39 % of total EU emissions in 2017 [89].

Chapter 6

6. Alternative propositions for further reduction of the emissions from the passenger vehicles

In the previous chapter we have seen the current emission state from road transport and progress towards the better air quality in Europe. But as seeing the progress from the emission from the passenger vehicles and the strict targets that EU commission is proposing it is rather confirmed throughout the analyses and the forecast that was made with the ARIMA (0,1,1) (see Fig. 5.9), we can see that the progress is rather slow and in addition further technologies have to be implemented to further decrease the emission level coming from the exhaust gasses of the passenger vehicles. Some proposals are described in the following Sections such as alternative fuels and their potentials, electromobility together with hybrid vehicles are mentioned as an alternative for further reduction of the emissions coming from the vehicles.

6.1 Alternative fuels - Biofuels

As mentioned in the previous chapter all EU-33 member states have national targets, which explain how they propose to comply with the overall target. In 2011, only 4 % of the energy consumed in transport was renewable, most of it from biofuels meeting the sustainability criteria, whereas it reached 7.4 % in 2017. Most Member States require significant further increases to reach the Directive's target for a 10 % share of renewable energy in transport by end of 2020.

The progress of individual Member States towards this target varies, with most requiring significant further increases. In 2017, Sweden was the EU country whose transport sector consumed the largest amount of energy from renewable sources. Sweden has already reached the 2020 target of a 10 % share of renewable energy in transport, as set by the RES (Renewable Energy Sector) Directive in 2011. Other EU Member States with high shares of RES from transport are Austria, France, Portugal, Ireland, Bulgaria, Germany and Slovakia, which all have shares above 7 %.

In general, the proportion of renewable energy used by the transport sector is growing but remains small. There are several reasons for the slow uptake of renewable fuels across the EU, including:

- Market uncertainty caused by delays in limiting the risk of greenhouse gas emissions due to indirect land use change;
- Relatively high abatement costs related to biofuels;
- Slow progress in the deployment of second-generation biofuels. [90]

When it comes to the divergence of the first-generation and second-generation biofuels and their slow progress in the deployment. First-generation bioethanol is produced using a process similar to that used in beer and winemaking by fermenting plant-derived sugars into ethanol. It includes the use of food and fodder crops, such as corn, sugar cane, sugar beet and wheat. The problem is that if these food crops are used to produce biofuels, food prices will increase, and in some countries, there may be shortages. Corn, wheat, and sugar beet in the form of fertilizers may also require high agricultural inputs, limiting the greenhouse gas reductions that can be achieved. Biodiesel made from transesterification from palm oil, rapeseed oil or other plant oils is also considered a first-generation biofuel. However, second-generation biofuels, technologies have been developed to enable the use of non-food biofuel feedstocks because of concerns to food security caused by the use of food crops for the production of first-generation biofuels [91]. The diversion of edible food biomass to the production of biofuels could theoretically result in competition with food and land uses for food crops.

The goal of second-generation biofuel processes is to increase the amount of biofuel that can be sustainably produced by using biomass consisting of residual non-food parts of current crops, such as stems, leaves and husks left behind once the food crop has been harvested, as well as other crops that are not used for food (non-food crops), such as switchgrass, jatropha, grass, whole crop maize, cereals and miscanthus, and also skins and pulp from fruit pressing and industry waste such as woodchips, etc.[92]

The issue addressed by processes of second-generation biofuel is to extract useful feedstocks from this woody or fibrous biomass, where the useful sugars are locked in by lignin, hemicellulose and cellulose. There is lignin, hemicellulose and cellulose in all plants. These are complex carbohydrates (sugar-based molecules). Lignocellulosic ethanol is produced by releasing cellulose sugar molecules with enzymes, steam heating, or other pre-treatments. Such sugars can then be fermented in the same way as the processing of bioethanol in the first sugars can then be fermented to produce ethanol in the same way as first-generation bioethanol production. The by-product of this process is lignin. Lignin can be burned as a carbon neutral fuel to produce heat and power for the processing plant and possibly for surrounding homes and businesses. In hydrothermal media, thermochemical processes (liquefaction) may produce liquid oily products from a wide range of feedstocks that have the potential to replace or augment fuels [93]. However, these liquid products fall short of diesel or biodiesel standards. Upgrading liquefaction products through one or several physical or chemical processes may improve the fuel use properties [94].

There are various studies, for instance, that ethanol is not a fuel option for Germany because there is not enough area for beet cultivation. Such views ignore the fact that Germany's dependence on imported crude oil is nearly 100% necessary for thermal engines and machinery. There are some crucial aspects to the transition from fossil to regenerative energy sources:

• Intensified introduction of oils and alcohols from plants, biomass, and waste from the wood, paper, and cellulose industries, independent of the shortage of fossil energy resources.

• Most prognoses show without doubt that thermal engines using regenerative fuels will be a larger part of future development, much more than other scenarios such as electric mobility (as shown in Fig. 6.1 for the year 2025).
Asia is expected to have the largest production of electric cars (2 million), as well as the highest sale of thermal-engine cars (32.6 million). A comparable European prognosis indicates a 0.7:22.4 million ratios. The following Table 6.1 shows the types of automobiles in use in Germany in January 2015 (in millions):

Gasoline	Diesel	Liquefied petroleum gas (bivalent)	Compressed natural gas (bivalent)	Electric	Hybrid	Total
29.8	13.9	0.5	0.08	0.019	0.1	44.4

Table 6.1. Types of automobiles used in Germany in January 2015 [95]

A prediction for similar types of cars for 2040 show a similar configuration:

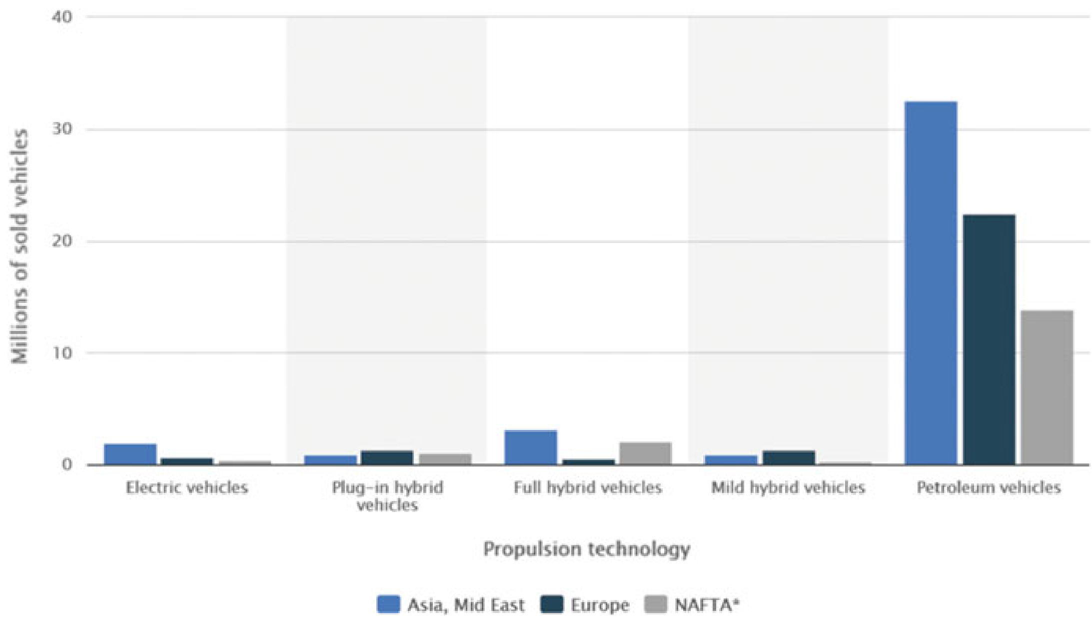


Fig. 6.1 Forecast for the worldwide selling of cars with conventional and alternative propulsion systems in 2015 (Source: www.statista.com, July 2015)

• Similar to the introduction of natural gas as a crude oil–based fuel in the automotive industry, the first step toward the use of other fuels will be bivalent on-board systems; this is a pragmatic reaction to the need for a supply infrastructure. There now are bivalent systems in use, such as compressed natural gas (CNG)/gasoline and liquid petroleum gas (LPG)/gasoline, with separate reservoirs and injection systems. Such bivalent systems are not required for alcohols and oils. Methanol and ethanol have properties that are similar to those of gasoline, allowing their storage (as a mixture) in the same reservoir, and their dosage with the same injection system. Engine operation with variable mixtures of gasoline, ethanol, and methanol is currently being explored. As well as hydrogen as an alternative fuel is currently being explored a lot and is advantageous properties. When burned correctly, its only emission is water vapor. However, there are two major problems with a hydrogen internal combustion engine. First, hydrogen is not as energy dense as other fuels, meaning that it is needed a whole lot of it to do a little bit of work.
Vegetable oils and diesel fuel have similar properties. However, oils must generally be esterified because of possible cooking during combustion and the tendency for mucilage production in the storage system. This explains why the processing of mixtures of diesel fuel and oil is tending to be moved from the reservoir to the refinery; in this way, hydrocarbon fuels with unitary molecular structures are obtainable.

However, the use of alternative fuels depends on the environment impact, the resources and the technical and technological base, but even more on their properties on board. Table 6.2 displays the characteristics of the fuels in relation to the engine and the vehicle itself. The most important correlations between fuel, engine and car are defined as follows:

• *Molecular fuel structure*: the fuel structure ($C_mH_nO_p$) affects both the structure and concentration of the combustion products, which depends on the carbon and hydrogen mass proportion in the combustion reaction. For instance, as extreme cases, the combustion of carbon leads to the maximum concentration of CO_2; on the other hand, the combustion of hydrogen results in pure water, without CO_2 [95].

• *Fuel density*: the volume and mass of the entire fuel and storage system (reservoir, ducts, valves) is determined by the fuel density at the required pressure and temperature. As shown in

Table 6.2, at ambient pressure and temperature, the gasoline, diesel, methanol, ethanol, and oil esters have similar densities.

LPG is stored on board vehicles generally at a pressure level of 0.5–1.0 MPa, which is possible and sufficient for storage of petroleum gas in the liquid phase [95].

Under ambient conditions, natural gas has a density which in this form does not allow its use in automobiles. At 20 MPa and ambient temperature, natural gas density is one-fifth of gasoline density allowing for onboard storage as CNG. Natural gas becomes liquid (LNG) at about 150°C and 0.1MPa, with half the gasoline density. Hydrogen storage on board an automobile remains a problem:

FUEL	STRUCTURE	DENSITY $[kg / dm^3]$	VISCOSITY (KIN.) $[cSt]$	FUEL ENTHALPY $[MJ / kg]$	STOICH. AIR-FUEL RATIO $[kgA / kg\ Fuel]$	MIXTURE ENTHALPY $[MJ / kg\ Mix]$	OCTAN NO / CETAN NO	VAPORIZATION ENTHALPIE $[KJ / kg]$ (25°C/0.1 MPa-LIQUID) (ts/0.1MPa-GAS)
HYDROCARBONS								
GASOLINE	C_mH_n ($<C_8H_{18}$)	0.72 - 0.78	0.6 - 0.75	44	14.6-14.7	3.9	91 - 99	350
DIESEL	C_mH_n ($<C_8H_{18}$)	0.78 - 0.84	3.5 - 3.9	43.2	14.5	3.8	50 - 54	270
NATURAL GAS (85-95% METHAN)	CH_4	0.141 (0°C/20MPa) 0.409 (-150°C/0.1MPa) 0.00079 (0°C/0.1MPa)	...	45	14.5	4.0	approx. 120	0.51 (GAS)
LPG 50% PROPAN; 50% BUTAN	C_3H_8/C_4H_{10}	0.00235 (GAS) (0°C/0.1MPa) approx. 0.5 (LIQUID) (0°C/0.5–1.0MPa)	...	46	15.5	3.8	98	386
ALCOHOLS METHANOL	CH_3-OH	0.792	0.75	20	6.47	3.5	106	1103
ETHANOL	C_2H_5-OH	0.785	1.5	26	9.00	3.5	107	840
HYDROGEN	H_2	0.009 (GAS) (-200°C/0.1MPa) 0.071 (LIQUID) (-253°C/0.1MPa)	-	120	34.3	3.0	-	436
VEGETABLE OILS RAPSED OIL	$C_mH_nO_pR_i$	0.92	68 - 75	35 - 39	12.4	3.5	38 - 44	...
RAPSED OIL METHYLESTHER		0.86 - 0.9	6 - 8	37.2	12.5	3.5	51 - 58	...
DIMETHYLETHER	CH_3OCH_3	0.00197 (GAS) (15°C/0.1MPa) 0.67 (LIQUID) (20°C/0.5MPa)	0.12 - 0.15 (20°C/0.5MPa)	28 (GAS) 27 (LIQUID)	9.0	3.5	55 - 60	400 (GAS)
INFLUENCE ON	exhaust gas components	storage on board	lubrication / coking	range	fuel dosage	torque	knock / flammability	cold start / mixture cooling / mass of air

Table 6.2. Properties of conventional and alternative fuels for automobiles [95]

$$pV = mRT \rightarrow mL = \frac{pV}{RT_L} \tag{6.1}$$

$$R = \frac{\bar{R}}{\bar{M}} \rightarrow R = \frac{8314}{2} = 4157[\frac{J}{kgK}] \tag{6.2}$$

$\boldsymbol{m}$	$[kg]$	Mass
$\boldsymbol{p}$	$[\frac{N}{m^3}]$	Pressure
$\boldsymbol{V}$	m^3	Volume
$\boldsymbol{R}$	$[\frac{J}{kgK}]$	Specific gas constant
$\boldsymbol{\bar{R}}$	$[\frac{J}{kmolK}]$	Universal gas constant
$\boldsymbol{\bar{M}}$	$[\frac{kg}{kmol}]$	Mass per kilomole

At the same pressure and temperature, hydrogen would be 14.5 times less than air in a reservoir with a given volume. By increasing the pressure or lowering the temperature, more mass is obtainable. Table 6.2 shows the outcome of one of these methods, cryogenic hydrogen storage at 20 K and 0.1 MPa. The hydrogen transitions from gaseous to liquid phase under such conditions, but its density remains just one tenth of that of gasoline. An increase in pressure, on the other hand, requires special techniques and materials. Hydrogen is the smallest of all molecules and can permeate a reservoir wall if the pressure difference between the reservoir and the surroundings is high and the wall material structure is conventional, such as a single layer of metal or plastic.

On the other hand, due to a local lack of oxygen for the numerous oil droplets, *viscosity* (as an effect of long and branched molecules) influences the combustion process. This is why coking happens when using pure plant oil diesel engines.

• *Heat value of the fuel*: The heat obtainable from the exothermic chemical reaction during combustion of 1 kg of the fuel depends on the fraction of the molecules of carbon, hydrogen and oxygen. The greater the fuel's heat value the lower the fuel mass for a comparable energy output in an engine [95]

• *Stoichiometric air-to-fuel ratio*: the air condition depends on the fuel structure, alike the heat value. Hydrogen requires the most air mass for a stoichiometric reaction. Alcohols contain a fraction of oxygen which ensures that air from the surroundings is reduced proportionately. For stationary engines, the mass flow of air can be adjusted to the injected fuel mass. However, the air mass is given geometrically in piston engines:

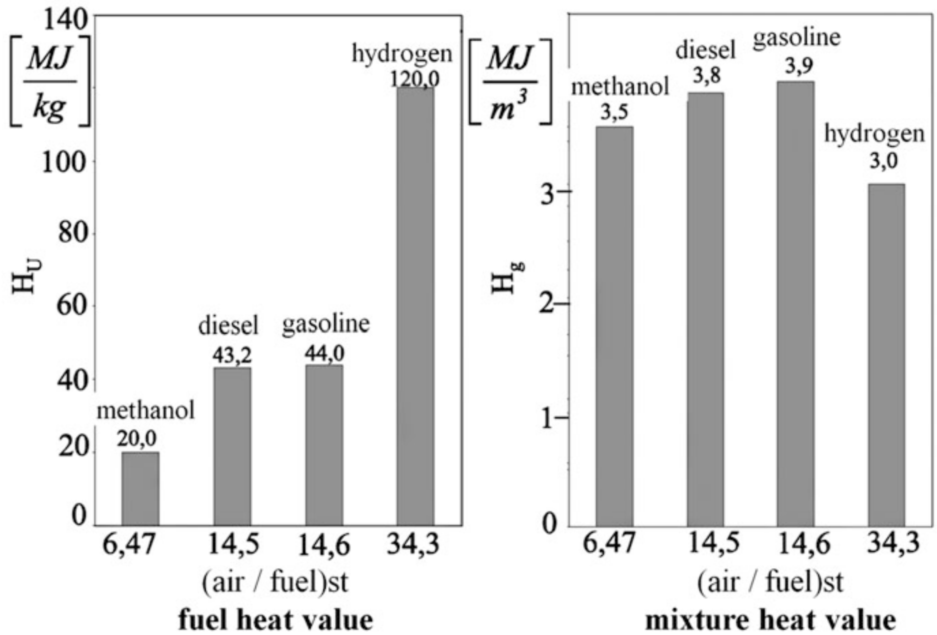


Fig. 6.2. Comparison of the heat values of fuel and fuel–air mixtures for different fuels [95]

$$m_L = \frac{pV}{RT_L}$$

In that event, the fuel mass must be adjusted according to the stoichiometric air / fuel ratio: the lower the requirement for stochiometric air, the higher the fuel mass. When methanol is replaced for gasoline, the fuel mass must be 2.2 times higher. This quantity can be modified by the fuel pressure, flow cross-areas at injection (i.e., by increasing the number of injectors) and opening duration of injectors. When gasoline is to be replaced with hydrogen, the fuel mass must be decreased by a factor of 0.42 [95].

• *Heat value of the fuel–air mixture*: A reduction in the injected mass of a fuel with a high heat value leads to a reduction in its energetic effect due to the high air/fuel ratio. Hydrogen's energy value is much greater than all other fuels ' heat value, so the cylinder has more heat intake and a higher power-to-volume ratio. Yet, due to the very high stoichiometric air/fuel ratio, the heat value of the fuel-air mixture is a little lower than for other fuels. Thus, the replacement of petrol by hydrogen in a piston engine results in lower torque, despite the higher combustion efficiency.

• *Octane and cetane number:* The knock resistance of the spark-ignition engines, measured by the number of cetane and by the number of octane and the ignitability of the compression ignition engines, depends on the molecular structure and volatility of the fuel and is highly variable for different fuels. From this prospective, methane and alcohol are more desirable than gasoline: a higher knock resistance allows for greater thermal efficiency and lower brake-specific fuel consumption. The ignitability of dimethyl ether (colourless volatile poisonous liquid compound) is noticeable in compression ignition engines, resulting from its high volatility and the oxygen content in its molecule. In opposite, pure, non-esterified oils have low ignitability due to their long molecules; the effect of transesterification on ignitability is remarkable, as shown in Table 6.2 [95].

• *Enthalpy of vaporization*. Fuel vaporization is an important criterion for the consistency of a fuel-air mixture and for the efficiency of combustion when using both fuel injection into the intake duct and direct fuel injection: the lower the fuel droplets and the greater the vapour ratio, the more effective the combustion process.

The characteristics of alternative fuels strongly influence the engine performance, enabling improvement of the processes involved such as air aspiration, fuel atomisation and vaporisation, fuel-air mixture formation and heat release during combustion. Therefore, switching to alternative fuel is good step because their properties considerably decreases harmful exhaust emissions (such as carbon dioxide, carbon monoxide, particulate matter and sulphur dioxide) as well as ozone-producing emissions. However, for instance even though there are no vehicle emissions other than water vapor using hydrogen as an alternative fuel and the fuel economy of the hydrogen is equivalent to about twice that of gasoline vehicles. Yet, acceptable range requires extremely-high-pressure, on-board hydrogen storage. Hydrogen is very expensive to transport and there is no infrastructure in place yet. Currently, hydrogen fuel is made from non-renewable natural gas in a process that creates enormous CO_2 emissions [96]. Therefore, a better understanding and improvements should be made of the alternative fuel regarding to their characteristics and processes involved such as air aspiration, fuel atomisation and vaporisation, fuel-air mixture formation and heat release during the combustion. And as well as better infrastructure, proficient understanding and developments of the sources that they are being derived from.

6.2. Electric Mobility

Taking into account the traffic flow, the greenhouse effect, pollutant emissions and noise emission, electric mobility seems to be the best alternative for public transport. However, these innovative features are prejudiced by extreme disadvantages regarding the sources of electric energy, how those batteries are manufactured and its storage on board vehicles. Generally, technical advances and the polarization of certain development directions will generally lead to solutions for complex problems.

In the last deceits with the successful upgrade of internal combustion engines, the low price of crude oil and its efficient conversion into mobility fuel, resulted in the temporary pause of electric car production due to the everlasting question of insufficient on-board electricity.
After the first oil crisis (1973) the industrial nations tried a new direction of energy policy towards alternative energy sources. This tendency was further emphasized by the second oil crisis (1979). The second Gulf War began in 1990, provoked by Iraq's annexation of Kuwait. The world's two largest exporters of crude oil were involved in this war. Therefore, a third oil crisis was supposed to cause serious changes in worldwide energy management. There was no crisis, but the second stage of electric mobility began (1992–2005). General acceptance, however, remained low because of the limited range of operations. The third and current stage of electric car development was induced mainly by the severe limitations on CO_2 emissions into the atmosphere. The development is based on engines, energy storage batteries, and on-board energy conversion fuel cells, and the development of a pure internal combustion engine appears to be on its last lap [95].

Electric vehicles are projected to be a key component of the transportation network in Europe, helping to reduce impacts on air quality and climate change. The largest potential reduction in GHG emissions lies during the use of the pure battery electric vehicles (BEVs). It will however depend on the electricity mix (i.e. the average mix of fuels used to produce electricity, which affects the carbon intensity of the electricity). Where, the life-cycle emissions from a BEV using renewable electricity could be nearly 90 percent lower than an equivalent internal combustion

vehicle (ICEV) [97]. BEVs charged with coal-generated electricity currently have higher life-cycle emissions than the ICEV.
Additionally, while BEVs have zero exhaust emissions and thus contribute to improved air quality, non-exhaust emissions (except from tyre, brake wear, and road abrasion) and energy production emissions are still present. In the future, with greater use of lower carbon electricity in the European mix, GHG emission savings, as well as advantages in terms of air quality of BEVs relative to ICEVs will increase [89].

Year	**Pure electric**	**Electric plug-in**	**Total vehicles**	**Total EV**
2011	7759	0	12829535	7759
2012	13986	9	12031054	13995
2013	24175	31167	11868737	55342
2014	37855	6818	12541978	44673
2015	56756	103553	13770826	160309
2016	64316	93707	14714327	158023
2017	97143	126898	15129296	224041
2018	148454	145898	14701753	294352

Table. 6.3 Increasing number in the market over the years for battery electric vehicles and plug-in hybrids, as well as comparison between total new passenger car registrations vs total electrical cars from 2011 – 2018 [Data source: Monitoring of CO_2 emissions from passenger cars - Data 2018, EEA,2018] [Stojchevski]

Electric cars are slowly penetrating the EU market. BEVs comprised 0.6 % of total new passenger car registrations in the EU in 2017. And from 2016 until 2018 that number more than doubled. Sales of plug-in hybrids (PHEVs) increased by 35 % in 2017 compared with 2016.

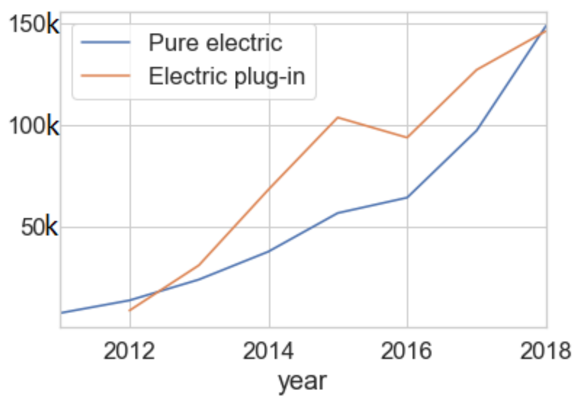


Figure 6.3. Battery electric vehicles vs plug-in hybrid over the years [Data source: Monitoring of CO2 emissions from passenger cars - Data 2018, EEA,2018] [Stojchevski]

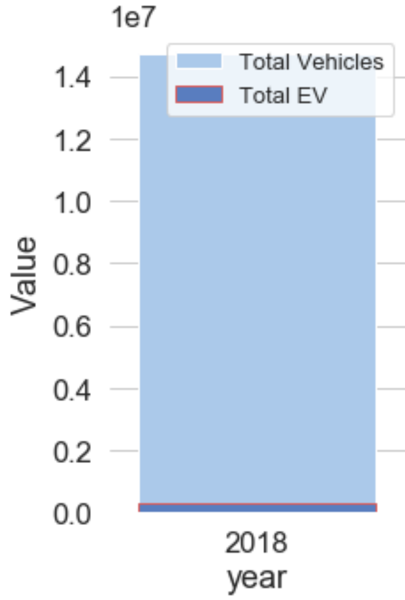


Figure 6.4. Total 14,701,753 vehicles in 2018 vs total of 294,352 electrical vehicles [Data source: Monitoring of CO_2 emissions from passenger cars - Data 2018, EEA,2018] [Stojchevski]

Many EU Member States have adopted financial incentives to purchase electrically charged vehicles and are pushing customers to choose cleaner vehicles. Finland had the highest sales of BEVs and plug-in hybrid (PHEVs) in new passenger car fleet in 2018 as well as the other Member States, Sweden, Belgium. Nevertheless, PHEVs accounted for only 0.8 percent of the EU's total new passenger car registrations in 2017. That is meanly because customers are not yet aware of their properties and as well as there are many consumer concerns over whether there are enough charging points along highways or parking lots as well as the strain on our power grids and electricity costs. As well as current expensiveness of the electric cars. Currently, as mentioned above there is very few electric cars on the road. Some cities in EU have more than others. Thus, the infrastructure needs to grow as more and more electric cars appear on our roads. In some of the bigger cities, the infrastructure is already suitable, and the number of publicly accessible charging stations has been growing rapidly in recent years [98].

Surely, the bill for electricity will go up but running an electric car would cost less than running a conventional petrol or diesel-powered car. This helps offset the high purchase price of electric cars over time. However, if 80% of all cars were electric by 2050, the EU's electricity consumption is likely to increase by about 10%. [99] Consequently, higher pollution if the electricity mix remain the same. Therefore, the electricity grid will also need to evolve, as more electric cars hit the road. That is a challenge, but the EU is already doing the same to integrate renewable sources into the grid.

Over the past decade, the EU as a whole has channelled billions of euros into relevant research and is approaching for a rapid expansion of charging infrastructure. It also invests heavily and promotes alternative fuel infrastructure, which includes chargers for electric vehicles, especially on the main European transit corridors. The EU is also pushing for the development of battery production in Europe, as electric car batteries are produced mainly in Japan, China and South Korea today. Lastly, the EU is also establishing common rules and standards for electric vehicles and charging infrastructure so there is convenient movement across Europe [100].

6.2.1 Hybridisation and electrification of cars

However, one of the reasons why electric cars are not yet dominating the market is that battery production capacity for motor vehicles is currently scarce, expensive and suffering from supply lags and challenges due to the electrical energy sources and their storage on board vehicles. This may change over time, but for some period securing an economic supply of battery production capacity will be pivotal to the successful commercialisation of electrified vehicles. Anyhow, electrification is a certain route to reducing or eliminating carbon dioxide (CO_2) emissions. Hence, the efficient deployment of available battery capacity between competing applications is vital for optimizing the reduction of CO_2 emissions.

So long as this shortage remains, a major concern at the moment is that the drive to pure electric battery vehicles (BEVs) could crowd out a more effective mass hybridization system. In other words, given the urgency of the need to reduce CO_2, paradoxically BEVs may not be the best way to achieve it with their supply chain, production capacity, and infrastructure and customer acceptance challenges. Such a rapid transition may be wounding for the environment and the declaration that BEVs are required to solve air quality problems is confusing the argument – cities in Europe can be brought into short-time fulfilment and reach the required targets with conventional internal combustion engines, with technology on the market today.

Before give into account what strategy mix represents the correct path, it is important to distinguish the categories of the hybrid vehicles in order to analyse their efficiency.
This common classification of hybrid configurations is made on the basis of the relative or absolute electric power part of the entire propulsion [95].

$$Hr = \frac{motor\ power}{motor\ power + engine\ power} \cdot 100\%$$

Consideration of the absolute form (P_{EM}) is more frequent, because of its simplicity. On this basis, parallel and mixed hybrids can be classified into the following categories:

- *Micro-Hybrids:* $P_{EM} < 6\ kW$

In such a configuration, a motor is not provided for direct propulsion but only for engine start at a power demand by the driver and for engine stop after a given idle period (start/stop function). Such motors, generally, operate at 12 V. The advantage of this solution is a reduction in fuel consumption of 3–6%

- *Mild Hybrids:* $P_{EM} = (6–20)\ kW$

These motors not only provide a start/stop feature but are also involved in propulsion during acceleration. The motor acts as a generator for the recuperation of braking energy, which is converted into electric energy and stored in the battery. These motors operate at a voltage of 42 V or 144 V. The combustion capacity decrease is between 10–20 percent.

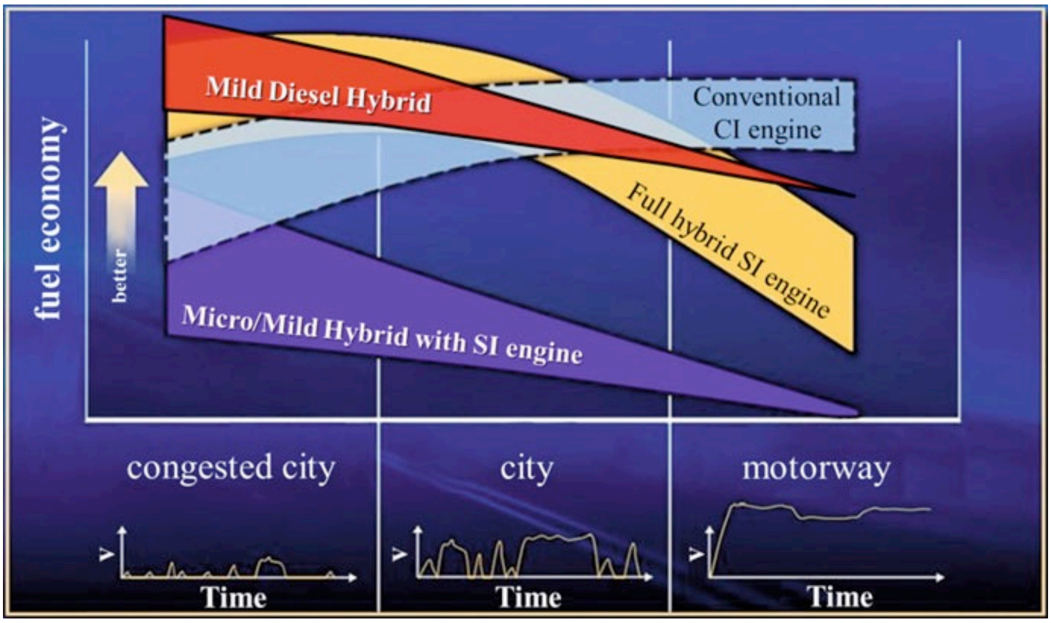


Figure 6.5. Influence of driving cycle on fuel economy when using micro, mild and full hybrids, in comparison with a conventional diesel engine [95]

- *Full Hybrids: P_{EM} > 40 kW*

In this category there are two function concepts:

–With only one motor, which together with the internal combustion engine ensures propulsion. (parallel hybrid)
–With additional motor besides the internal combustion engine. ("power split" or mixed hybrid)
In some cases, one of the motors, with the engine decoupled, will ensure propulsion for the vehicle by itself. The voltage in such setups is 250 V. The estimated fuel consumption decrease is between 30–40%. However, reducing fuel consumption when using micro, mild or full hybrids depends heavily on the driving cycle. Shown in Figure 6.5.
As illustrated in Fig. 6.5, micro and mild hybrids are very advantageous for urban driving, but their efficiency on country roads, and particularly on motorways, is reduced. Full hybrids are highly efficient in urban traffic, being more competitive than other hybrid types and diesel engine propulsion. However, a complete hybrid on country roads or motorways has almost no benefits as opposed to a diesel engine. The diesel engine clearly represents the best choice on motorways, regarding the fuel efficiency.

- *Plug-in Hybrids:*

A plug-in hybrid electric vehicle is a hybrid electric vehicle whose battery can be recharged by plugging it into an external source of electric power, as well as by its on-board engine and generator. PHEVs typically use batteries to power an electric motor and use another fuel, such as gasoline, to power an internal combustion engine. PHEV batteries can be charged using a wall outlet or charging station, by the internal combustion engine, or through regenerative braking. The vehicle typically runs on electric power until the battery is depleted, and then the car automatically switches over to use the internal combustion engine.

There are many configurations and solutions for full hybrid propulsion systems. The variety of brands and the number of configurations is vast, Figure 6.6.

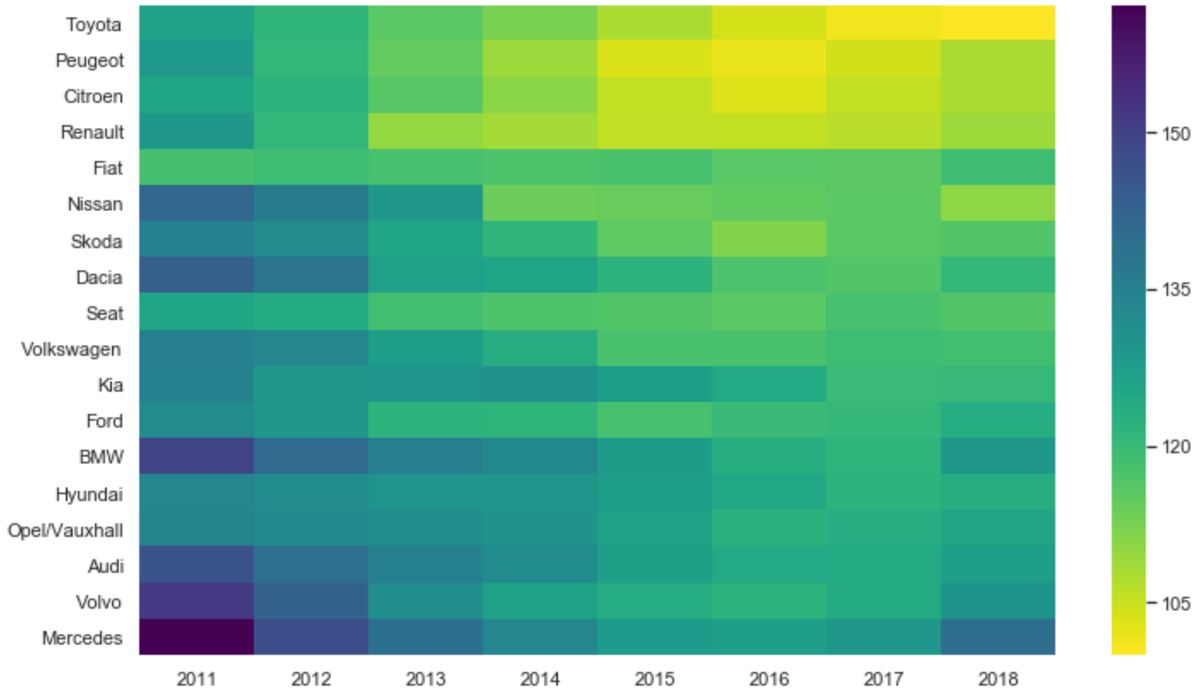


Figure 6.6. Average CO_2 emission of Selected Car Brand in g/km [Stojchevski] [Data source: Section 4.3, Data: e)]

Since the introduction of the Toyota Prius in the beginning of 2000s, hybrid cars have spread rapidly, with most brands producing hybrid cars of varying types. Today, most car manufacturers will produce hybrid models of their most popular cars, as well as hybrid-only models. Navigating the diverse hybrid vehicle market can be challenging due to the number of options available, and it is important to understand what certain vehicles have to offer.

However, at the moment the focus on the car manufacturers comes down to how to achieve it as cost-efficiently and quickly as possible the road transport CO_2 emission reduction. And the question that is being ask is how best to deliver road transportation's part in meeting the Paris climate change targets. The apparent consensus is to transition to pure electric vehicles as rapidly as possible. But is this singular focus better than a combined strategy employing a wide variety of hybrid electric vehicles?

The issue with the pure electric vehicle approach is that the switch will be slow, BEVs need extremely large batteries to provide acceptable consumer utility, just as the battery capacity is a scarce resource today. As reducing cumulative CO_2 emissions is important for climate change, many more hybrid vehicles, would eliminate a far greater volume of CO_2 than applying the scarce battery resource to a smaller number of BEVs [101]. This strategy also helps to minimize essentially slow fleet turnover, with the average age of cars on the road being over twelve years.

The following analysis takes into account the mild, full and plug-in hybrid vehicles tested in both Europe and the United States by Emissions Analytics. Each hybrid is paired with its nearest internal-combustion-engine-only equivalent car, often the same make and model with a similar engine capacity. Then measures the difference between the hybrid and its conventional-engine pair in average CO_2 emissions over the standard on-road cycle.

The first table focuses on mild and full hybrids, excluding plug-ins, and shows the average tailpipe CO_2 reductions that can be achieved with vehicles currently on the market, or at least models sold over the last seven years. Due to the typically higher CO_2 emissions starting point of US cars, the average US reduction is greater than in Europe, and often the new hybrid technology is introduced earlier on the US market. Five of these 95 hybrids are diesels.

	Average hybrid battery size	Average non-hybrid CO_2	Average hybrid CO_2	CO_2 reduction from hybrid
	kWh	**g/km**	**g/hm**	**%**
EU	1.2	184	143	-23%
US	1.2	214	141	-34%
Average	1.2	203	143	-30%

Table 6.4. Average CO_2 reduction from hybrid and non-hybrid vehicles over standard on-road cycle [101]

To place this 30% reduction in framework, the EU's post-2021 CO_2 reduction target for passenger vehicles is 37.5% by 2030. More than three-quarters of that target is doable with only non-plug-in hybridisation, with technology currently available in the market. In addition, with fourth generation hybrids now entering the market, hybrid advantages will further increase. It is possible, in combination with plug-in hybridisation and other design innovations, that the target could be achieved without the need for fully electrification.

Showing output distribution by individual model, the following chart relates the efficiency of CO_2 reduction by battery size. Mild and full hybrids are the most effective on average, but there are substantial differences within the class–showing that the variety of individual vehicles remains at least as important as generic powertrains.

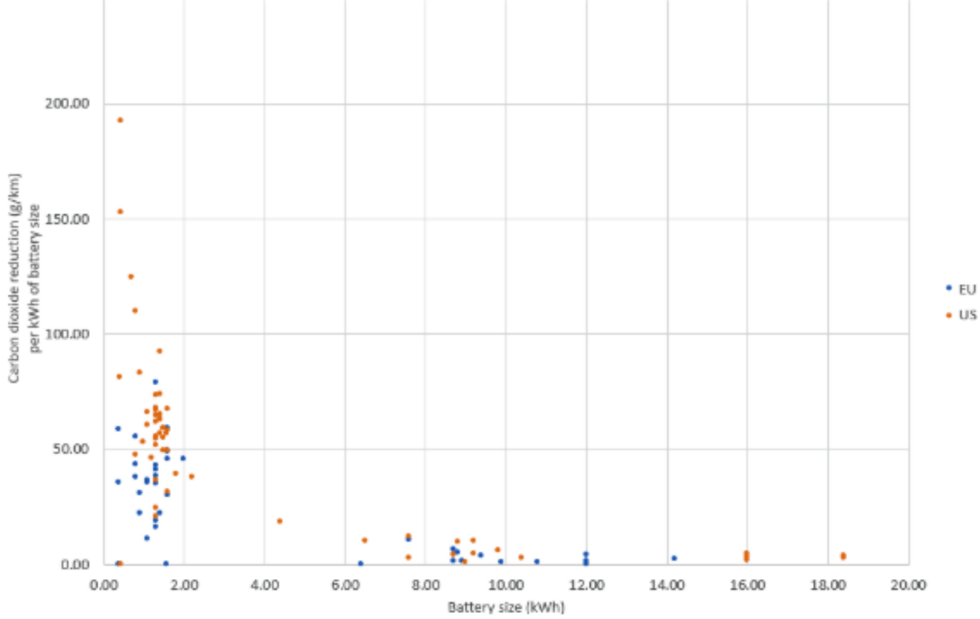


Figure 6.7. CO_2 reduction per kWh of battery size [101]

In terms of the trajectory to total CO_2 reduction, a switch from gasoline internal combustion engine to full gasoline hybrid can reduce emissions by 34% [101]. As it will take time to increase the supply of full hybrids, there are two routes to short-term CO_2 reduction that are feasibly more rapid. First, a switch from gasoline to latest technology of diesel internal combustion engine in practice reduces CO_2 emissions by 11% at the tailpipe. However, they have higher emissions of NO_x and much higher emissions of particulate matter than petrol engines. Yet in terms of trajectory a second step then to a diesel mild hybrid delivers a further 6% reduction. The final switch to full hybrid delivers another 16%, making 34% in total. Alternatively, a direct switch from gasoline to gasoline mild hybrid can deliver 11%, followed by a further 23% in moving to full hybrid. Therefore, there are immediate-term options for significant CO_2 reduction, involving both gasoline and diesel powertrains [95].

Fuller electrification would be needed at any regulatory level beyond the 37.5 per cent reduction in the fleet, as there are limitations to the overall CO_2 reduction that hybrids can deliver. By 2030, however, the EU would have had more time to develop improved, cleaner electricity generation capacity, enhanced distribution grid and fix the supply chain issues around the scarce materials in batteries. Should not be ignored as well the need for public awareness and acceptance in order to remove barriers to implementation. The alternative scenario by 2030 is that the quality and price of renewable electricity could have plummeted to a point at which hydrogen-fuel cell vehicles can become economic feasible, which avoid some of the environmental and geopolitical issues created by large-scale battery production.

In summary, this data strongly suggests that policy promoting one development solution arbitrarily may be fundamentally inefficient, and maybe even the wrong possible solution. A better approach would be to use real-world data to enable the growth of competing technologies as they can show genuine CO_2 reductions, delivered as soon as possible.

Chapter 7

7. Conclusion of the thesis

Development scenarios for automobiles worldwide are rather controversial. Regardless of their current efficient technologies, such catalysts and filters and obtaining maximum emission reduction, the development of this technologies is still not enough to reach the EU targets and further reduce the emission from the exhausting fuels.

The basic conclusion is that when it comes to climate change and air quality, electric and hybrid cars are the best alternative for transport in urban areas and clearly preferable to petrol or diesel cars. Contrary to some public doubts and uncertainties about the environmental benefits of electric cars, the science is increasingly clear. Even with the current electricity mix in Europe, which still includes a lot of electricity from coal, there are clear benefits. These benefits will further increase going forward, as Europe uses more renewable energy in the future and if there is better attention to reuse, remanufacturing and recycling. There have been many scientific studies on the lifecycle impacts of electric cars. It is important EU legislations needs to be improved better at reusing and recycling electric cars and their components to minimise the impact of their production on the environment. The end of life phase is particularly important for electric cars. They contain a lot of metals and other critical raw materials that can consume large amounts of energy to process and involve sometimes toxic substances in their production. So, if the recovering can be made from existing cars and reuse them it's a big benefit. If we can take a whole component like a battery and use it in a different application, this can really reduce the overall environmental impact significantly.

Firstly, it needs to be certain that the electricity supply used for making and running electric cars comes from renewable sources. This is really the biggest single influence factor on their environmental and health performance. Secondly, these cars need to last long. Squeezing the mileage out of every electric car that is being produced is vital. So, if they are just driven for 70 000 kilometres (km) and then scrapped, their overall environmental performance does not look so good compared to conventional cars because of the extra energy used for their production – more than that of a conventional car. But once driven them for 150 000 km or more, the comparison strongly favours electric cars. Finally, when an electric car needs to be scrapped, it needs to be made the most of its materials.

It is very important to say that no car will ever be 100 % clean. The arrival of the electric car does not change that. The message that needs to be carried is that if a person really needs to use a car, an electric or hybrid car is the better choice for the environment. However, using public transport or simply walking or cycling to work will always be much better for the environment. It can deliver a 65 per cent emissions reduction during peak times and a 95 per cent reduction in emissions during off peak times from the commuters that make the shift. At current occupancy rates for cars a full bus load of passengers can take more than 40 cars off the road and a full passenger train can take 500 cars off the road [102]. Based on 2004 occupancy figures for cars and buses the fuel consumption of buses for every 100 passenger kilometres was 2.5 litres and the fuel consumption of cars for every 100 passenger kilometres was 7 litres. A ten per cent shift to bus passenger transport from cars would reduce greenhouse gas emissions by more than 400,000 tonnes a year and every million passenger kilometres on public transport, instead of cars, saves 45,000 litres of fuel [102]. Moreover, the emissions savings figures for trains, if extrapolated from the figures delivered for bus by a ten per cent shift to rail passenger transport from cars could save as much as 4Mt of emissions a year [103]. In the long term reduced dependency on cars will lead to further reductions in emissions from road transport.

A car is still a car; replacing one with another type is not going to solve transport problems like congestion. Electric motors are simply more efficient than combustion engines, so more of the energy put in the battery ends up being used to drive the car. Especially when driving in cities, electric vehicles waste less energy. Also, there are simply no tailpipe emissions of air pollutants such as nitrogen oxides and particles. There are still particles from braking and from tyre wear, but overall there is less than from a petrol or diesel car. Electric vehicles can also bring down noise, especially at lower speeds they are less noisy than conventional cars.
Health-wise, the main benefit is related to air quality. There will still be some air pollution from the electricity that goes into electric cars, but this typically comes from power stations which might have better pollution controls than could be implemented in a conventional car and are usually located further away from densely populated areas.

For the end is important to be mentioned that actual developments confirm the tendency for polarization of car types in relation to regional, geographical, economic, ecological, and social conditions. This complex structure of the energy management between propulsion and energy supply on board an automobile has now received a new dimension, caused by globalization of the development and production of automobiles. The main aspects of this complex structure are:

The demand for specific propulsion systems for specific automobile classes and regional characteristics marks the discussed development trends, the very concrete interpretation of “demand” being the purchase behaviour.

The resources of energy and raw materials are another independent factor to consider during development. The trend to transition from fossil to regenerative energy sources is more developed than predicted a decade ago, whereas the consideration of hydrogen as the ideal fuel of the future is now much more moderate.

Compatibility with the environment traces the limits of development, independently of demand or resources. A drastic reduction in CO_2 emission (or its recycling in a natural cycle) and pollutant-free operation are conditions that remain paramount for every technical innovation.

Cost effectiveness does not always allow solutions that seem feasible from the point of view of demand, resources, or compatibility with the environment. A compact car with a fuel cell fed by hydrogen obtained from photovoltaic facilities would be an exemplary solution if considered in terms of demand, resources, and environment. Nevertheless, the obvious expense means that there is no chance of a large series production of such cars. An example confirms this fact: some time ago it was demonstrated in a very impressive manner that an automobile with fuel consumption of under 3 l/100 km is technically feasible. But, the price of this car corresponds to the price of a large luxury car; therefore, series production is not effective [95].

Technical feasibility is an additional challenge: a good example is, once again, the utilization of hydrogen. Even though production without emission of CO_2 and at moderate costs is possible, on-board storage remains a problem. Hydrogen has the smallest molecular mass and therefore the largest gas constant of all elements in nature. This results in the lowest density at comparable pressure and temperature, in the same volume of a tank. The penetration of such small hydrogen molecules through any wall structure at a given pressure potential and its inflammability in ambient air at concentrations above 4% remain physical problems, despite technical progress.

Traffic problems can affect any development plan, even if encouraged from the point of view of demand, resources, environment, economy, and technical feasibility. The Mayor of a European megacity remarked some time ago during a conference of specialists: "cars without emissions of pollutants and noise would be excellent for any city—but I have no more streets for them."

Safety, comfort, aesthetics, and communication are reliable functions of the automobile, partially imposed by law and partially required by customers. Obviously, the autonomy of an electric car with battery could be improved if the car mass were drastically reduced. Miniature vehicles with a weight of 250–300 kg are good testimonies of this. However, safety and comfort are also reduced; thus, such vehicles are more recommended for urban use.
The creation of automobiles with appropriate propulsion systems for different utilizations requires, especially in the given conditions of modular functions, taking into account globalized construction and production, which are complex [95]. Technical knowhow and a technological base are the first conditions that decide the destiny of a promising car or propulsion concept. Furthermore, the social structure, cultural specifics, and political and economic stability are intrinsic conditions for the planned development or production in a given region.

The most basic solution for air pollution is to end its root causes: quit coal and move away from fossil fuels, replacing them with clean, renewable energy. In the short-term, use of hybrid vehicles or biofuels is also advantageous solution. There are many intermediate solutions for air pollution. The use of renewable energy sources, introducing cleaner fuel standards and switching to electric vehicles are only a few of the measures that can be implemented. However, all of these solutions require governments to recognize the impact of air pollution on public health and the economy and take action accordingly. As well as global consciousness of each individual to be aware of the air pollution and start contributing better technologies or simply if possible, using public transport, walking or cycling to work will always be much better for the environment. As individuals, we can contribute by supporting leaders who push for clean air and responsible steps on climate change.

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Appendices

1D	One Dimensional
2D	Two Dimensional
ARIMA	Autoregressive integrated moving average
ARMA	Autoregressive–moving-average mode
AT	All Type
BEV	Battery Electric Vehicles
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon Dioxide
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DPF	Diesel Particulate Filters
EEA	European Environmental Agency
EGR	Exhaust Gas Recirculation
EGR	Exhaust Gas Recirculation
EU	European Union
EV	Electric Vehicles
GDI	Petrol Direct Injection Engines
GHG	Greenhouse Gas
GPF	Gasoline Particulate Filters
HC	Hydrocarbons
IC	Inner Combustion
ICEV	Internal Combustion Vehicle
IPCC	Intergovernmental Panel on Climate Change
JATO	Car Comparisons & Automotive Market Research
LNG	Liquid Natural Gas
LNT	Lean NO*x* Trap
LPG	Liquid Petroleum Gas
LRTAP	The Convention on Long-range Transboundary Air Pollution
MMR	Monitoring Mechanism Regulation
MSE	Mean Square Error
NECD	National Emissions Ceilings Directive
NEDC	New European Driving Cycle
NH_3	Ammonia
NO_x	Nitrogen Oxides
NSRC	Nitrogen Oxide Storage and Reduction Converter
NT	New Type
OBD	On-Board Diagnostics
PAH	Polynuclear Aromatic Hydrocarbons
PEMS	Portable Emission Measurement System
PHEV	Plug-in Hybrids
PM	Particulate Matter
PMR	Power-To-Mass
PN	Particulate Number
RDE	Real-World Driving Emissions
RMSE	Root Mean Square Error (RMSE)
SCR	Selective Catalytic Reduction
SO_2	Sulphur Dioxide

SUV	Sport Utility Vehicle
TD	Turbo Diesel
TDI	Turbocharged Direct Injection
TERM	Transport and Environment Reporting Mechanism
TWC	Three-Way Catalyst
UHC	Unburned Hydrocarbons
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
VDA	German Automotive Industry Association
VVT	Variable Valve Timing
WLTP	Worldwide Harmonised Light Vehicle Test Procedure