BRNO UNIVERSITY OF TECHNOLOGY

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF MECHANICAL ENGINEERING

FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF AUTOMOTIVE ENGINEERING

ÚSTAV AUTOMOBILNÍHO A DOPRAVNÍHO INŽENÝRSTVÍ

DECREASING OF GENERATION OF EMISSIONS OF ALREADY PRODUCED PASSENGER CARS WITH SPARK IGNITION ENGINES IN EU

SNÍŽENÍ TVORBY EMISÍ U STÁVAJÍCÍ FLOTILY ZÁŽEHOVÝCH OSOBNÍCH AUTOMOBILŮ V EVROPĚ

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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VEDOUCÍ PRÁCE

BRNO 2021

Assignment Bachelor's Thesis

Institute:	Institute of Automotive Engineering
Student:	**Dominik Hálek**
Degree program:	Engineering
Branch:	Fundamentals of Mechanical Engineering
Supervisor:	**Ing. Jiří Bazala**
Academic year:	2020/21

As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Decreasing of generation of emissions of already produced passenger cars with spark ignition engines in EU

1 Brief Description:

Stricter emission standards for new cars is only a partial solution to environmental issues. It may seem more efficient to equip already manufactured cars that meet older emission standards with a system that reduces the production of these unwanted emissions.

2 Bachelor's Thesis goals:

Emission standards overview for passenger cars.
Passenger cars statistics operating in the EU and theoretical calculations for the necessary emission reductions in relation to the forecast of new passenger car sales with European Commission regulations.
Analysis of current solutions offered as retrofits for emission reduction.
Critical evaluation of retrofit solutions as an effective solution to the global issue of passenger cars.

3 Recommended bibliography:

STONE, Richard. Introduction to internal combustion engines. 3rd edition. Warrendale, Pa.: Society of Automotive Engineers, 1999. 641 s. ISBN 0768004950.

Deadline for submission Bachelor's Thesis is given by the Schedule of the Academic year 2020/21

In Brno,

L. S.

prof. Ing. Josef Štětina, Ph.D.

Director of the Institute

doc. Ing. Jaroslav Katolický,

Ph.D. FME dean

ABSTRACT

This bachelor thesis is dealing with reduction of unwanted emissions of passenger cars given by EU standards. The thesis is focused particularly on idea of fitting of already produced passenger cars with spark ignition engines, that meet older emission standards, with a system, that can reduce this unwanted emissions coming from the exhaust pipe. Outcome of this work is summary of basic retrofits, theoretical calculation of reduction of emissions for cars equipped with selected retrofit and decision about using retrofits as an appropriate component for decreasing of emissions, especially CO_2 emissions.

KEY WORDS

Emissions, CO_2, NO_x, retrofits, vehicle, passenger, WLTC

ABSTRAKT

Tato závěrečná práce se zabývá snížením nežádoucích emisí u osobních automobilů podléhající normám daným Evropskou unií. Práce je zaměřena především na myšlenku vybavení stávajících osobních automobilů se spalovacím motorem, které splňují starší normy, systémem, který zredukuje tyto škodlivé emise pocházející z výfuku. Výstupem je shrnutí základních retrofitů, teoretický propočet snížení emisí u aut vybavených vybraným retrofitem a zhodnocení použití retrofitu jako prostředku pro snížení emisí, speciálně CO_2 emisí.

KLÍČOVÁ SLOVA

Emise, CO_2, NOx, retrofity, vozidlo, osobní, WLTC

BIBLIOGRAPHY

HÁLEK, Dominik. *Snížení tvorby emisí u stávající flotily zážehových osobních automobilů v Evropě.* Brno, 2021. Dostupné také z: https://www.vutbr.cz/studenti/zav-prace/detail/129499. Bakalářská práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Ústav automobilního a dopravního inženýrství. Vedoucí práce Jiří Bazala.

DECLARATION OF AUTHENTICITY

I declare that my bachelor thesis on the theme: “Decreasing of generation of emission of already produced passenger cars with spark ignition engines in EU” is my own work and that all the resources, that I have used or quoted, have been listed at the end of thesis.

In Brno 20. 5. 2021 ……..……..…………………………………………..

Dominik Hálek

ACKNOWLEDGEMENT

I would like to thank to my supervisor of my bachelor thesis Ing. Jiří Bazala for his valuable advice, helpfulness and patience during consultations.

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INTRODUCTION

In these days is the fight against producing of emissions one of the biggest goals of human kind. The negative effect of emissions is visible – it causes air pollution, smog in towns and both has negative effects on human's health. Road traffic by itself is responsible for 11.9 % of greenhouse gas emissions [61]. Therefor the European Union is trying to fight against it with strict emission standards, that has to accomplished every new passenger car that want to be road legal in the EU. In the effort of reducing emissions on very low levels, EU came out with grants for people that want to buy an electric car. But production of an electric car is not zero-emission, as I will explain later in the thesis, and also the electricity that powers these vehicles is not from renewable sources only (except Norway). So is it the right idea for future? Will it have the right impact on environment that EU wants?

And that gives idea to my bachelor thesis. Because the transformation of all European's fleet of passenger cars to electric would last for decades, costs enormous amount of money and might not have the right impact on the environment. So instead of waiting for that will happen, let's try to figure out some solution, that can reduce emissions of already produced cars in motion on European roads. Some of these solutions are already on market e.g. CNG, LPG, ethanol, hydrogen or water injection. Fitting older cars with these equipment can reduce unwanted emissions significantly and it costs much less compared to buying of new electric car even with EU grants. And mainly, it can have smaller impact on the environment.

My bachelor thesis will try to take that idea, find the basic retrofits for reduction of emissions and do some calculations of possibility and practicability of that project on European's fleet of passenger cars with spark ignition engines. And if the idea will be accomplishable and the European Union starts support that, it can reduce the emissions in shorter period of time with less harmful impact on the environment.

1 EUROPEAN EMISSION STANDARDS - EURO

European emission standards can be defined as an acceptable limits of emissions that come from exhaust system of a new vehicles sold in European Union or EEA (European Economic Area) [3]. The first European emission standard was introduced in 1970, but nowadays Euro standards as we know them now were introduced in 1992 with Euro 1 [2]. The main purpose of introduction of Euro standards was improving air quality. From 1992 began series of Euro standards till Euro 6, which is valid in these days. The emissions started to be reduced by development in technologies fitted in vehicles during the time to keep up with legislation. The technologies such as direct fuel management, variable valve timing and sophisticated systems, that managed the engine, played the main role in accomplishing these Euro standards [1]. All that helped to reduce some of the pollutants by 96 % compared to 1992 limits [2].

1.1 HISTORY OF EURO STANDARDS

European regulation in area of emission standards began in July 1992 when the first Euro 1 (EC93) was introduced. Euro 1 required the switch to unleaded petrol and made fitting catalytic converters compulsory for all new cars. After 4 years came the Euro 2 (EC96) where was decided that gasoline and diesel vehicles will have different values for their limits. Otherwise there was a reduction of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide (NO_x). Euro 3 (EC2000) came in the year of 2000 and brought separation hydrocarbons and nitrogen oxide (HC + NO_x) limits for petrol vehicles to hydrocarbons (THC) and nitrogen oxide (NO_x) as well as adding a separate nitrogen oxide (NO_x) limit for diesel cars. And the warm-up period was removed from testing procedure [3]. Euro 4, that came in year 2005, was focused on reduction of emissions from diesel cars and especially on decrease of particulate matter (PM) and oxides of nitrogen (NO_x) [2]. After another couple of years the Euro 5 was introduced in 2009 and tightened the limits of particular emissions for diesel cars. One of the biggest news was introduction of Diesel particulate filters (DPFs) for diesel vehicles. The DPFs capture almost 99 % of particular matter and became necessary for every new diesel car to meet Euro 5 requirements [3]. For the first time there was introduced limits of particular matter (PM) for gasoline cars, but it was applicable for engines with direct injection only. Euro 5 also came with limit on particle numbers (PN) for diesel engines in addition to the particle weight limit for new type approvals from September 2011 and from January 2013 for all new diesel cars [2]. The main aim of Euro 6 limits, introduced in 2014, was reducing NO_x emissions from diesel cars, because the results of scientific studies have showed a connection between NO_x emissions and respiratory problems [3]. These target can be achieved with some different systems fitted in vehicles working on same principle that car makers have introduced e.g. Selective Catalytic Reduction (SCR) – in which is a liquid reducer injected through catalyst into exhaust. That causes a chemical reaction which converts nitrogen oxide into water and nitrogen. Other systems used in diesel cars to meet Euro 6 requirements are – Exhaust Gas Recirculation (EGR) or NO_x absorber (Lean NO_x Trap) [2],[3].

1.2 TECHNICAL STANDARDS

In the following tables is summarized the development of emission limits for Euro standards from 1992 to these days. The dates listed in tables are valid for new type approvals. European Commission also adds a second date for first registration which is mainly a year later unless indicated otherwise [4].

Table 1.1: EU emission standards for diesel Passenger Cars (M_1,M_2) [4].

Tier	Date	CO [g/km]	HC + NO_x [g/km]	NO_x [g/km]	PM [g/km]	PN [-]
Euro 1	1992.07	2.72	0.97	-	0.14	-
Euro 2	1996.01	1.00	0.70	-	0.08	-
Euro 3	2000.01	0.64	0.56	0.50	0.05	-
Euro 4	2005.01	0.50	0.30	0.25	0.025	-
Euro 5	2009.09	0.50	0.23	0.18	0.05	6.0x10^11/km
Euro 6	2014.09	0.50	0.17	0.08	0.005	6.0x10^11/km

Table 1.2: EU emission standards for gasoline Passenger Cars (M_1,M_2) [4].

Tier	Date	CO [g/km]	HC + NO_x [g/km]	NO_x [g/km]	THC [g/km]	NMHC [g/km]	PM* [g/km]	PN [-]
Euro 1	1992.07	2.72	0.97	-	-	-	-	-
Euro 2	1996.01	2.20	0.50	-	-	-	-	-
Euro 3	2000.01	2.30	-	0.15	0.20	-	-	-
Euro 4	2005.01	1.00	-	0.08	0.10	-	-	-
Euro 5	2009.09	1.00	-	0.06	0.10	0.068	0.005	-
Euro 6	2014.09	1.00	-	0.06	0.10	0.068	0.005	6.0x10^11/km

*direct injection only

1.3 EURO 6C

Euro 6 standard was released in 2014 and since than there has been a couple of modifications of it - Euro 6c, Euro 6d-TEMP and the last with the name Euro 6d. The official limits for each pollutant remained identical which means that the change was in the testing procedure.

Euro 6c was introduced in September 2017 and it contained transition from NEDC (New European Driving Cycle) testing procedure to WLTP (World harmonized Light vehicles Test Procedure). Both are laboratory tests but the WLTP new procedure is more precise, realistic and more comparable with the real-world measurements. The main aim of it was to give more realistic reflection of real-world driving behaviour [18]. From the technical perspective, the distance during the testing procedure is bigger, average speed is higher, cycle time is longer and also the car reach higher maximum speed compared to NEDC test cycle [19]. Alongside with WLTP came the RDE (Real Driving Emissions) for comparison to make sure the reality matches the controlled environment [20].

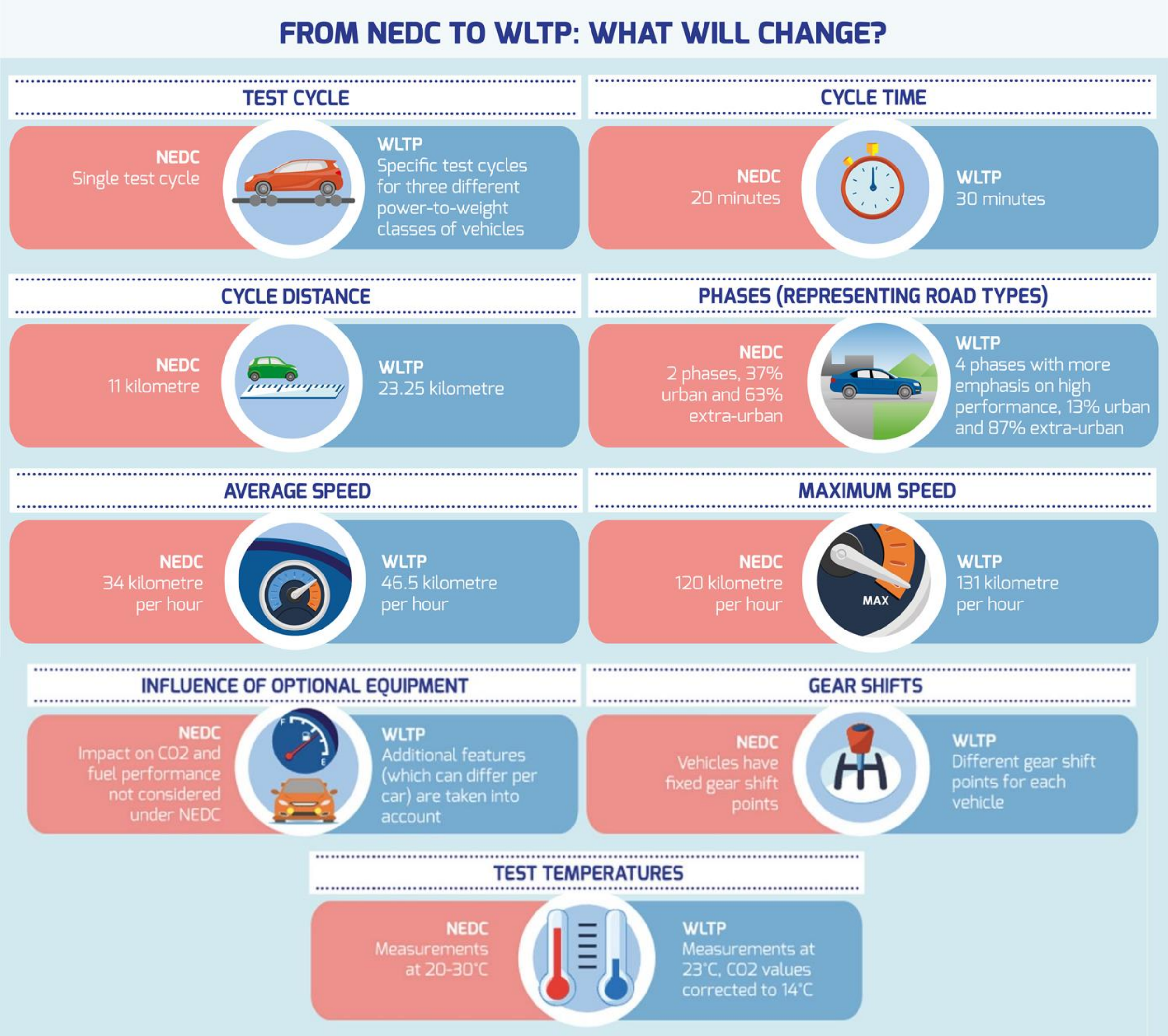

Figure 1: From NEDC to WLTP: What will change? [19].

1.4 EURO 6D-TEMP

The Euro 6d-TEMP (from the word "temporary") was introduced in September 2017, the same date as a Euro 6c, but it took effect for first registrations after two years in September 2019. In these Euro standard is the RDE part not only for comparison but it is a part of a testing procedure. According to the Euro 6 limits the value of NO_x emissions for gasoline vehicles is 60 mg/km and for diesel vehicles 80 mg/km. The Euro 6d-TEMP allows during the RDE testing procedure the deviation of 110 % which is equal to the Conformity Factor (CF) of 2.1. That means that the gasoline cars can emit 126 mg/km and diesel vehicles can emit 168 mg/km of NO_x emissions in real-world measuring. But after complaints of some European cities such as Madrid, Paris and Brussels the General Court of the European Union decided that it is not so technically difficult for car-makers to meet the laboratory limits in real-world measurement [20].

1.5 EURO 6D

The Euro 6d (full name is Euro 6d ISC-FCM) came in January 2020 for new type approvals and it is valid from January 2021 for first registrations. The Conformity Factor was reduced from 2.1 to 1.43. Which allows maximum NO_x emissions of 85.8 mg/km for gasoline cars and 114.4 mg/km for diesel cars. And the idea is reduce the Conformity Factor in subsequent years to 1.0, which means that the real-world results will be equal to laboratory measurements [21].

17th April 2019 was set the Regulation 2019/631 which says that the European Commission will publish through implementing acts a special list containing specific emission target and an average specific emissions level of CO_2 in the calendar year for each manufacturer. This list will also include the difference between that year and the preceding year to analyse whether the manufacturer has succeed with the specific emission target for the preceding calendar year. For year 2020 the limit was set to maximum of 120 g/km for carbon dioxide emissions. Since 1 January 2021 the limit have decreased to maximum of 95 g/km. This amount depends, among other things, on average weight of vehicles, so the value is certainly different for each manufacturer – for example for Daimler, producing more heavier vehicles, is the limit 103 g/km whereas for Peugeot, which produces smaller cars, is the limit set for 91 g/km [21].

This EU regulation also includes a set of fines for manufacturers that will exceed their average emission limit. The amount was set on €95 for each gram over the limit and it is charged for every car sold. Volkswagen recently has felt how unpleasant this fines are. Their limit for 2020 was set to 99.3 g/km but unfortunately they closed the year on average level of 99.8 g/km of carbon dioxide emissions. And this just 0.5 g/km cost Volkswagen enormous €100 million, because of their huge volume of sales [21].

EU rewards manufacturers for producing of low-emission vehicles (below 50 g/km of CO_2) which helps car makers to achieve the specific emission target given by European Commission. In 2021, the Regulation counts each low-emission car as 1.67 cars and it should drop to 1.33 in 2022. This directive pushes car makers to sell more hybrids and electric cars and therefore supporting their sales [21].

Regulation 2019/631 also allows formation of car makers to make possible to pass strict emission target. It is especially for manufacturers that not offering electric or hybrid vehicles. For example the FCA (Fiat Chrysler Automobiles) made a formation with Tesla because their cars producing zero emissions and thanks to this merger the FCA avoided paying huge fines for not achieving specific emission target. They paid Tesla some fee for letting FCA to merge with them but it is considerably lower than the fine they will have to pay for breaking of the EU regulation [21].

But these new emission limits are not applied on all vehicles. There are some exceptions as an armoured vehicles or cars for transporting disabled persons. And also the manufacturers with less than 1,000 registrations per year are exempted from all of these regulations [21].

Figure 2. RDE measuring on Volkswagen Arteon [22].

1.6 POST-EURO 6

Air pollution is still a big problem. Even with these strict regulations that has been developed since 1970s is the air pollution responsible in European Union for more than 400,000 premature deaths per year. According the World Health Organization (WHO) is the air pollution connected with occurrences of cancer, stroke, diabetes or Alzheimer's disease [5].

Studies also showed that the real-world NO_x emissions from diesel cars between Euro 3 and Euro 5 regulations remained basically unchanged. Nevertheless there is reduction of NO_x emissions form diesel cars accomplishing Euro 6 but the real-world NO_x emissions are still several times above the limit. On the other hand the petrol vehicles NO_x emissions decreased almost equivalently with Euro 6 limits [5].

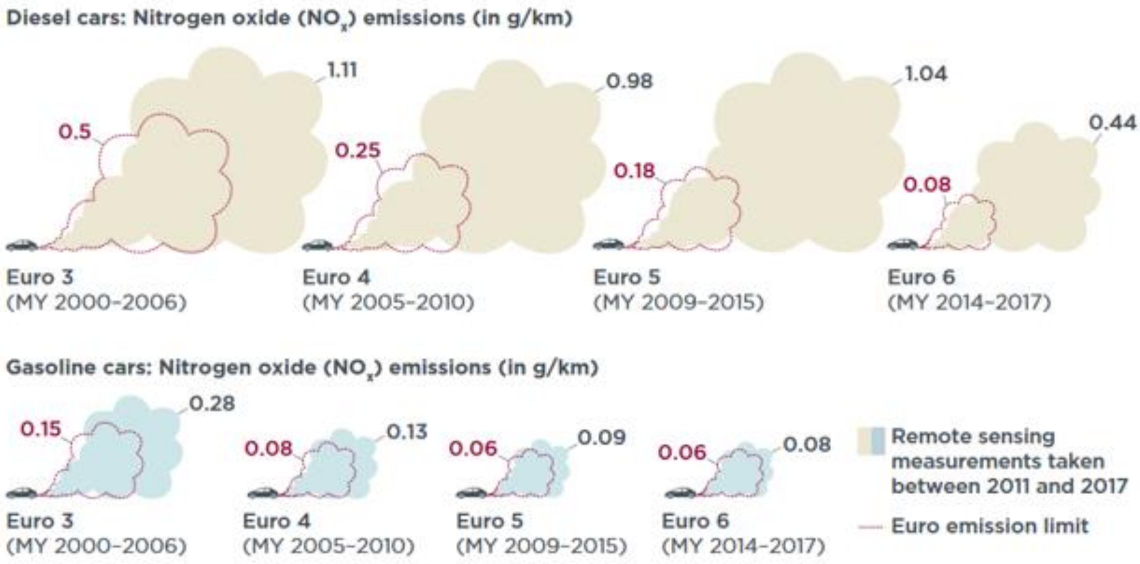

Figure 3. Nitrogen oxide (NO_x) emissions estimated via remote sensing of the on-road fleet, from Euro 3 to Euro 6, for EU passenger vehicle [5].

Therefore the European Commission has started the work on new emission regulations that will come after Euro 6. It is focused on strengthened selected emissions limits, on new air pollutants that can be regulated, on the change in testing regimes or on data evaluation methods. The Euro 6 standard is more than 5 years old and it doesn't reflect the technological development that has been accomplished in recent years [5].

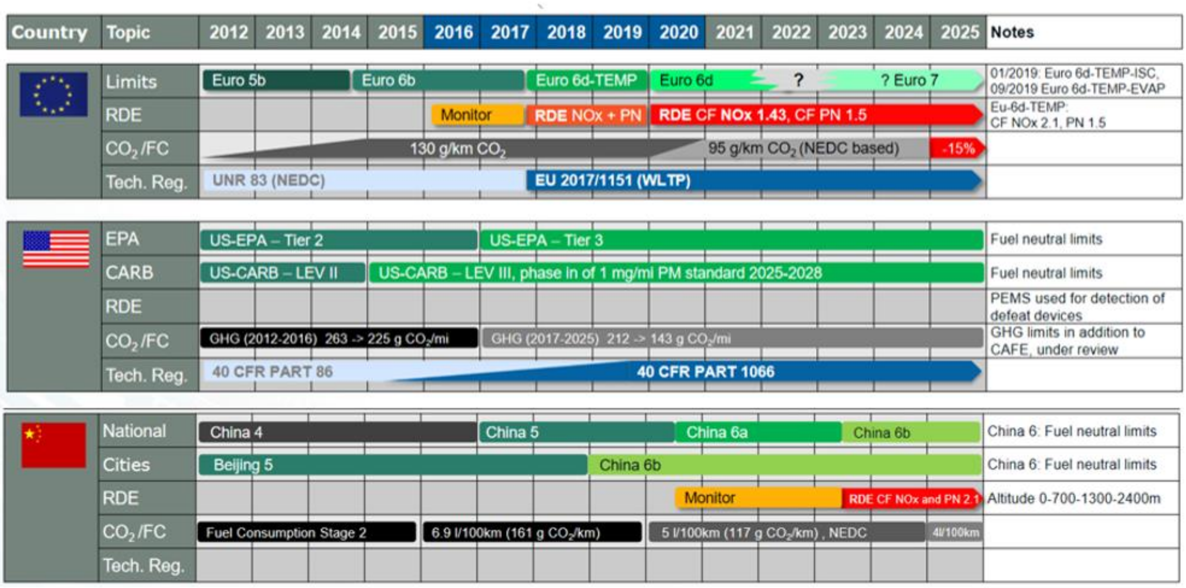

Figure 4. Comparing emission standards in EU, USA and China [36].

Interesting is look on the other big vehicle markets in the world and their regulations – China and United States of America. Figure 5 shows that the EU regulations are really lenient compared the regulations from China and USA. China 6a reflects the current emission limits in China and the China 6b reflects the emission limits applicable from July 2023. The U.S. Tier 3 are the limits set for the year 2025. What is also important that the China 6 and U.S. Tier 3 regulations are both fuel-neutral, that means there are no different limits for petrol and diesel vehicles. The U.S. Tier 3 doesn’t also make difference between passenger cars and light commercial vehicles (LCVs). Instead of European regulations where the LCVs is allowed to have 60 % higher emissions that the passenger car with the same maximum weight [5].

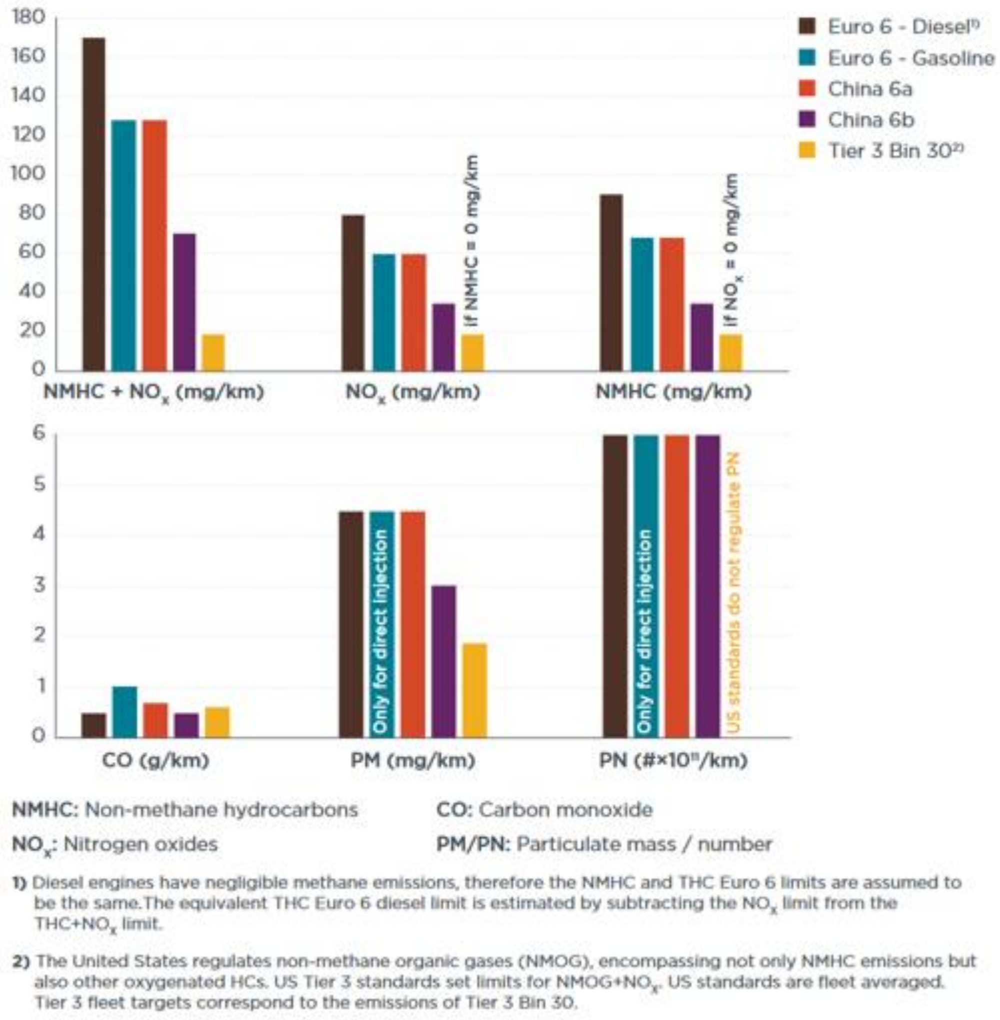

Figure 5. LDV emission limits according to the Euro 6, China 6 and U.S. Tier 3 standards [5].

If we take for example the NO_x emissions, the Euro 6 limit for diesel cars is set for 80 mg/km. Whereas China 6b limit for year 2023 allows only 35 mg/km per vehicle. The U.S. Tier 3 NO_x limits are connected with non-methane organic gases (NMOG) which covers wider range of species than non-methane hydrocarbon limits (NMHC). U.S. Tier 3 standards allows 19 mg/km of combination of NO_x and NMOG only [5]. Penalties for car makers for violating US Tier 3 standards are set to $5.50 per tenth of a mile per gallon [37]. The penalties for car manufacturers in China that violate the limits has not been published.

That clearly shows that EU regulations need to be improved to keep up with regulations on the other two largest passenger vehicle markets. The EU needs to introduce fuel-neutral and application-neutral limits. In area of unregulated pollutants can European Commission set limits for ammonia emissions, aldehyde emissions or for CH_4 and N_2O emissions [5].

The European Commission's goal is to make Europe until 2050 the first carbon-neutral continent. There are some middle steps for achieving these goal and the first one is introducing an Euro 7 limit. The works on them will continue during the year 2021 and Euro 7 should be introduced at the end of 2025. Rumours said that no combustion engine will pass these strict limits which means that from 2025/2026 only hybrid or electric vehicles might be allowed to be sold. In addition after some rumours about how strict the new Euro 7 standard will be, manufacturers such as Audi, Volkswagen or Daimler has announced that they will stop developing a new series of internal-combustion engines. They will only continue to develop and modify current combustion engines to meet the new Euro 7 limits and focus on developing and manufacturing electric vehicles [38].

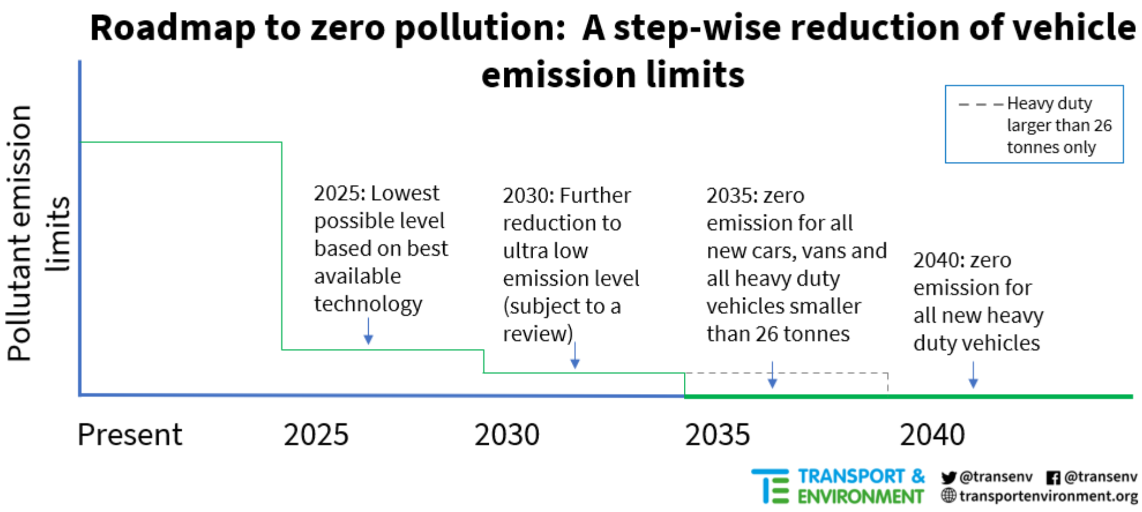

Figure 6. A step-wise reduction of vehicle emission limits [39].

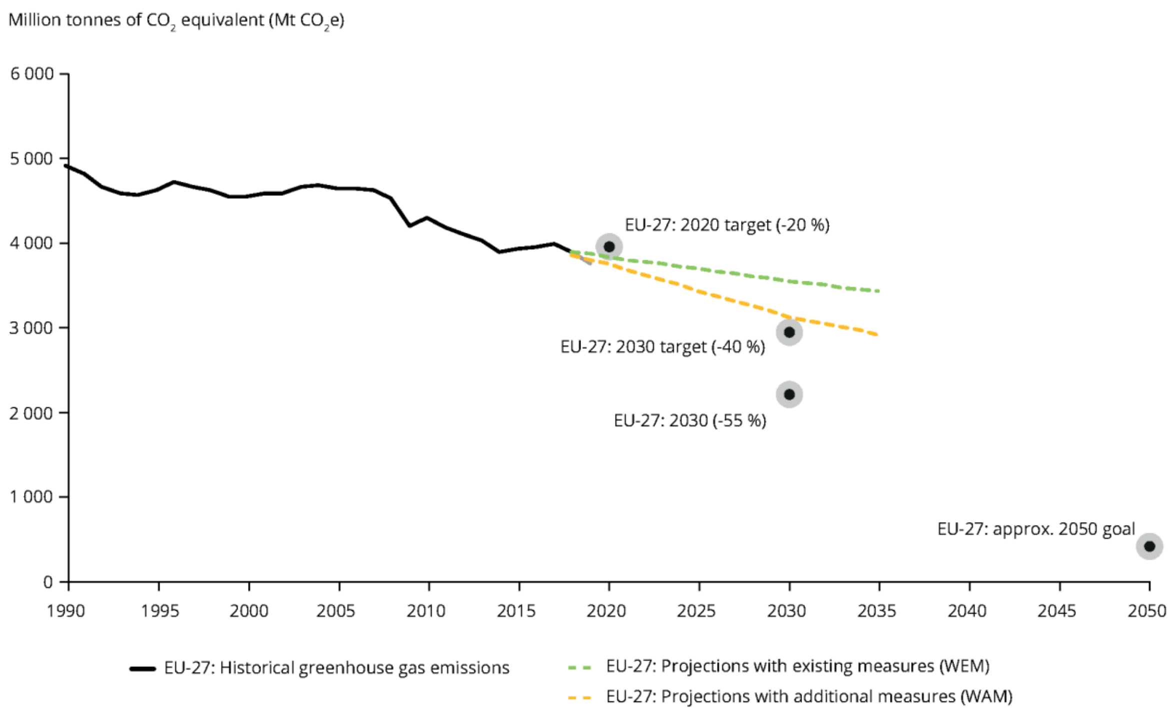

Figure 7. Greenhouse gas emission targets and trends in the EU, 1990-2050 [40].

2 RETROFITS

Retrofits are devices that can be fitted in the vehicle to decrease fuel consumption and also reduce the emissions coming from the exhaust. To the typical basic retrofits belong - compressed natural gas (CNG), liquefied petroleum gas (LPG) and ethanol. According to the EU reports from 2019, these three types (CNG, LPG and ethanol) creates only 1.7 % of new car registration in European Union [6].

2.1 COMPRESSED NATURAL GAS (CNG)

Compressed natural gas (CNG) is the gaseous product of petroleum and it is the first product that is separated from the distillation process. It is mainly made up of methane (CH_4), furthermore nitrogen, carbon dioxide (CO_2) and propane [7]. CNG is produced by compressing the conventional natural gas to less than 1 % of the volume that occupies at standard atmospheric pressure. It is lighter than the air and it has to be stored in rigid containers under the pressure of 20-25 MPa [8]. Calorific value of CNG is 50 MJ/kg [43].

We can differentiate two types of CNG cars:

1) Dedicated CNG vehicle,
2) Bi-fuel retrofitted gasoline vehicle.

2.1.1 DEDICATED CNG VEHICLE

Dedicated CNG vehicle have spark ignition engine that is working on CNG only. CNG has a very high octane number around 120-130 which allows the engine operate with higher compression ratio and therefore enhance the engine thermal efficiency of 10 % above than efficiency of gasoline engine. The dedicated CNG engines can have the efficiency up to 35 % compared to the 25 % of a normal gasoline engine [8].

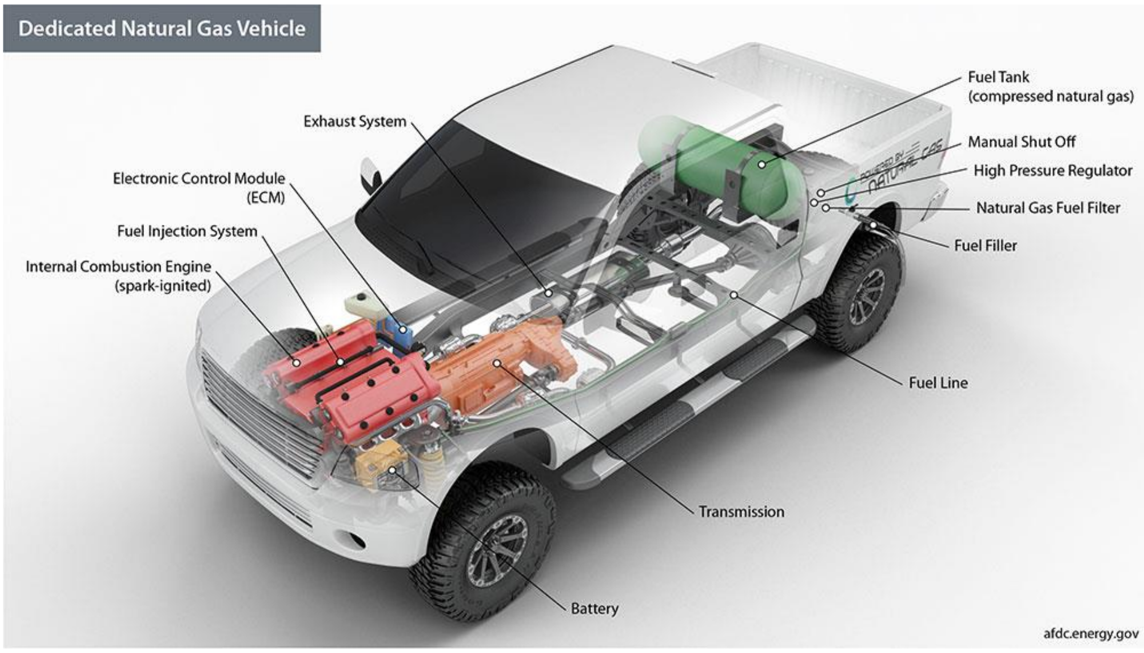

Figure 8. Dedicated Natural Gas Vehicle [9].

2.1.2 BI-FUEL RETROFITTED GASOLINE VEHICLE

Bi-fuel engine means that can run on both substances – CNG or gasoline. The type of the engine is basic spark ignition engine and the driver can easily select on which fuel he wants to run on by flipping the switch on the dashboard. Any of existing gasoline cars can be actually converted to bi-fuel. From the technical perspective the combustion properties of CNG are different from regular fuel like gasoline. CNG has a longer ignition delay time due to low propagation speed. So using the same gasoline fuelled engine for CNG, that means the combustion duration becomes slightly longer and it requires advanced spark timing. The bi-fuel vehicles are generally optimized for CNG with the ignition timing rather advanced to deal with slower burning rate of methane [8].

Unfortunately in retrofitted vehicles to bi-fuel cannot be achieved so high efficiency as at dedicated CNG vehicle. The bi-fuel engines will not take advantage of high octane number because the compression ratio will be set to level that gasoline requires [8].

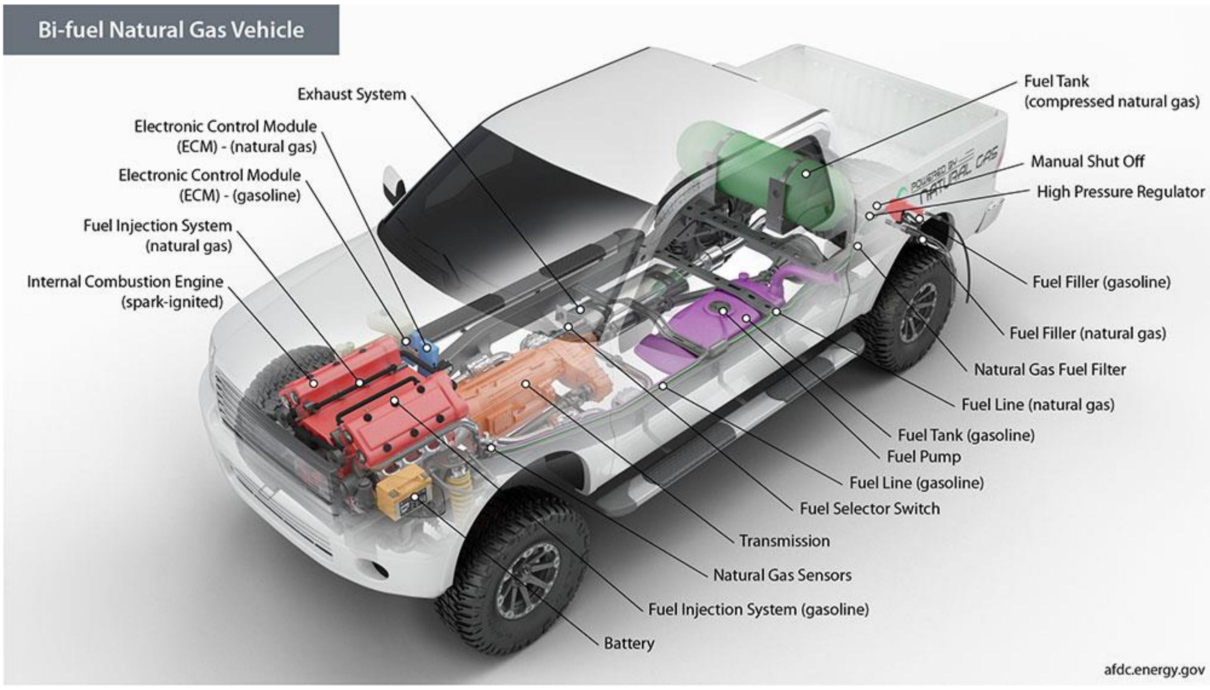

Figure 9. Bi-fuel Natural Gas Vehicle [10].

2.1.3 COSTS

Conversion of the car from only gasoline to bi-fuel needs to be done by well-qualified experienced worker. In Czech Republic there are many companies that can convert your car into CNG bi-fuel. The average price of the conversion is approximately between €1400-2500. It depends on how many cylinders the engine has and at the type of injection that customer will select. But for normal 4-cylinder engine it is between €1500-1600 (average €1,550).

Table 2.1 shows that the average prices in selected countries are different. In Czech Republic is the tax from CNG about 11 % of the whole price [60], whereas tax from gasoline is about 66 %. In Germany makes the tax about 68 % of the price of gasoline and about 59 % in case of diesel [59].

Table 2.1: Average price of gasoline and CNG in selected states in EU to 6. March 2021 [11].

Country	Gasoline price [€/l]	CNG price [€/kg]	CNG per litre gasoline equivalent [-]
Belgium	1.440	0.848	0.589
Czech Republic	1.177	0.961	0.816
Germany	1.511	1.034	0.684
Italy	1.657	0.987	0.596
Netherlands	1.780	1.031	0.579
Poland	1.086	0.362	0,334
Spain	1.337	0.623	0.466
Average	**1.427**	**0.835**	**0.581**

Now we show as an example the Škoda Octavia. In Škoda configurator mode you can choose from various engines including gasoline, diesel, CNG and mild-hybrid. For compare I chose the gasoline engine 1.5 TSI with 110 kW. The average fuel consumption given by manufacturer is 5.3 l/100km. Now imagine that the car will do 15,000 km per year. If we take the average gasoline price in Czech Republic calculated in Table 2.1, by these conditions the year costs will reach €936. And now the 1.5 TGI G-TEC engine with 96 kW. The average fuel consumption given by manufacturer is 5.5 m^3/100 km [29]. Because the Table 2.1 shows prices for one kilogram of CNG we need to convert it to kilograms – 1 kg of CNG equals 1.4 m^3 [13]. That means the fuel consumption is about 3.9 kg/100 km. Calculation with average price of CNG in Czech Republic from the Table 2.1 shows that by the same conditions (15,000 km per year) the year costs will reach €562. That is a saving around 40 % of running costs. And by these calculations the savings will be around €374 per year and therefor the beginning investment will return after 4 years. In other European countries will be the year savings bigger, because there are bigger differences between prices of gasoline and CNG than in Czech Republic.

2.1.4 Emissions

If we take a look in brochure on production of CO_2 emissions, according to Škoda, the 1.5 TSI produces 122 g/100 km whereas the bi-fuel 1.5 TGI G-TEC engine running on CNG only produces 99 g/100 km [29]. That means the CNG produces almost 19 % fewer carbon dioxide emissions than gasoline engine.

Emission savings of CNG was also the main theme of study of scientist from Department of Mechanical Engineering Aristotele University of Thessaloniki in Greece. They took two cars that meet Euro 6 standards – first was diesel and second was bi-fuel (gasoline/CNG). In case of the bi-fuel vehicle there were tests running on gasoline or CNG only. In the study was used two types of driving regimes – one complying on Real Driving Emissions (RDE) regulation and second characterized by more aggressive driving. In the laboratory the WLTC (Worldwide harmonized Light vehicles Test Cycle) was used, applying the realistic road load of the vehicles. And one of the results was following: "Natural gas can reduce CO_2 emissions significantly compared to both gasoline and diesel due to its lower carbon content and its higher calorific value."[12].

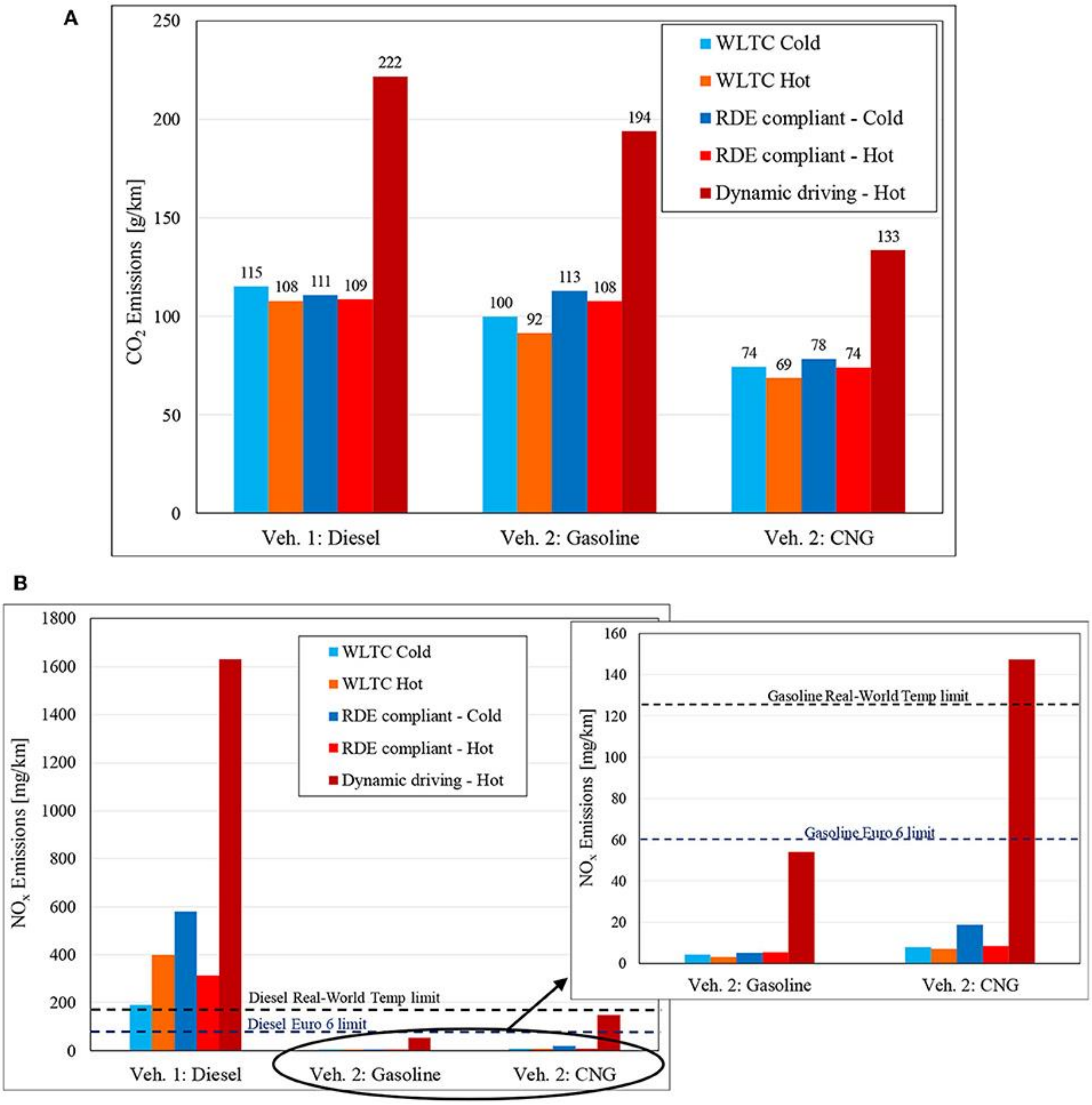

*Figure 10. **(A)** CO_2 and **(B)** NO_x emissions of the vehicles tested under different driving conditions [12].*

If we skip the WLTC laboratory tests and will focus on the real driving conditions which is "RDE compliant - Cold and Hot" and "Dynamic driving – Hot" we can see decrease of emissions of CO_2 by the CNG mode about 31 % compared to gasoline mode. It is obvious that running on CNG can decrease CO_2 emissions significantly but on the other hand the NO_x emissions are slightly higher than from gasoline mode. But they are still under Euro 6 gasoline limit with only exception which is Dynamic driving regime [12].

Another study from 2010 took the 1.6l 4-cylindre spark ignition engine and converted it into natural gas bi-fuel engine. Researchers measured the influence of that conversion on brake horsepower and production of different emissions. They used two settings for engine:

- 50 % throttle position with a speed range from 1,500 to 5,500 RPM at a constant increment of 500 RPM,
- 80 % throttle position with a speed range of 1,500 – 5,500 RPM at a constant increment of 500 RPM [63].

They discovered that the retrofitted vehicle produces slightly less brake horsepower because the peak at 50 % throttle position was 27.70 kW for gasoline and 22.67 kW for CNG. For 80 % throttle position 54.97 kW for gasoline and 50.44 kW for CNG. That means that the difference is 18.2 %, respectively 8.2 %. From that we can assume approximately decrease of brake horsepower around 13 % for retrofitted vehicles [63].

HC emissions were on average of 22.14 % and 29.71 % lower than gasoline for the 50 % and 80 % throttle position. The carbon monoxide emissions (CO) were on average 45.50 % and 29.87 % lower than gasoline in the same 50 % and 80 % throttle positions. In case of CO_2 emissions there was also big reduction – 30.88 % for the 50 % throttle position and 34.97 % for the 80 % throttle position. From that we can assume average reduction of CO_2 emission around 32.93 % for converted vehicles into bi-fuel. Only one increase appeared in case of NO_x emissions. 41 % more NO_x emission were observed for the 50 % throttle position and 38 % more for the 80 % throttle position [63]. That leads to conclusion that the retrofitted vehicle into CNG bi-fuel has slightly less brake horsepower, but it is able to reduce HC, CO and CO_2 emissions coming from exhaust. The only one problem is increase of NO_x emissions.

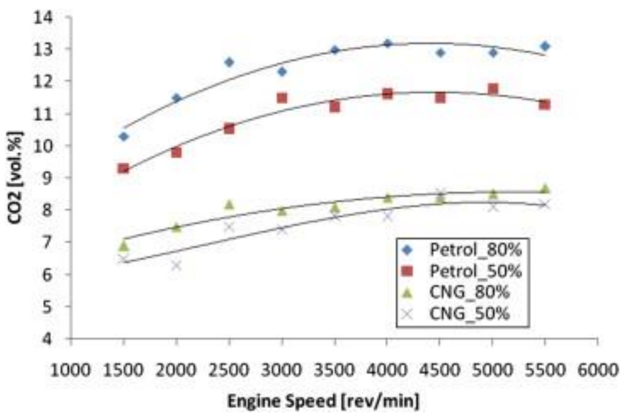

Figure 11. Carbon dioxide (CO_2) emission over a speed range at 50 % and 80 % throttle condition for gasoline and CNG [63].

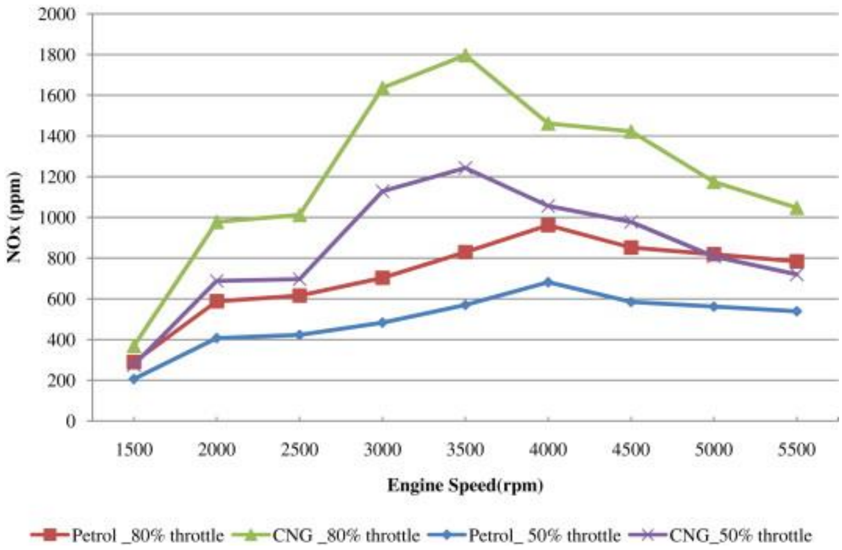

Figure 12. Nitrogen oxides (NOx) emission at 50 % and 80 % throttle condition for gasoline and CNG [63].

2.1.5 ADVANTAGES OF CNG

+ **Lower overall running costs** – according to March 2021 the price of 1 litre of gasoline in Germany was €1.511 whereas price of 1 kg CNG was €1.034 (Table 2.1).
+ **Produce fewer unwanted emissions** – can lead to reduction of CO_2 emissions around 32 %.
+ **Bigger safety** – because CNG tanks and fuel lines are regulated by strict standards, in case of accident the CNG will spread in the environment because is lighter than the air and has also higher auto-ignition temperature (540°C) than gasoline [17].
+ **Cleaner engine** - CNG minimizes harmful carbon deposits when combusted, that results to cleaner and more efficient engine [15].

2.1.6 DISADVANTAGES OF CNG

– **Less space in boot and bigger weight** - because the CNG fuel tank has to be stored in a boot space and that also leads to increasing of weight of the vehicle [15].
– **Smaller network of CNG refuelling stations** – CNG refuelling stations is fewer than normal petrol stations (For example in Czech Republic there is 192 of CNG refuelling stations but 2,837 of classic petrol stations) [14].
– **Smaller driving range** – depends on size of CNG fuel tank but the typical driving range is between 300 - 500 kilometres [16].
– **Slightly less power** – car that is retrofitted into CNG bi-fuel can have its power between 5-10 % lower than original gasoline one [16].

2.2 LIQUIFIED PETROLEUM GAS (LPG)

Liquified petroleum gas known as LPG is a mixture of propane, butane and other substances in small amount. LPG is obtained as a by-product during the refining of petroleum. The mixture is liquified by cooling to low temperature or by compressing. In process of liquefaction is its volume reduced 260 times compared to gaseous form. LPG is similar to gasoline, because it has approximately the same energy value of 45 MJ/kg. In gaseous form is heavier than the air which means in case of leakage the LPG spreads to the lower floor areas. There are some added components to make LPG smellable in case of leakage. Its octane number is 106 up to 110 so its higher than gasoline octane number. LPG is usually stored in rigid steel tank placed in a car boot under the maximum pressure of 0.1 MPa. For safety reasons the tank is filled up to 80 % of its volume [23]. Propane is popular to use in light-, medium- or even heavy-duty vehicles such as vans, taxis or school buses. LPG low carbon contamination can lead to longer engine life and also propane performs well in cold condition, because it is in gaseous form when it enters the fuel injection system which provides from many issues connected with classic cold starts [26].

2.2.1 DEDICATED LPG VEHICLE

LPG dedicated vehicle operate with classic spark-ignition combustion engine. There are two types of fuel-injection systems available – vapor or liquid injection. In both cases is the LPG stored in liquid form in low-pressure tank. In vapor-injection vehicles, the liquid gas travels across the vehicle in fuel line into engine compartment where the liquid is converted into vapor by regulator or vaporizer. In liquid-injection vehicles, the liquid is not vaporized until it reaches fuel injector, which leads to more precise control of fuel delivery and it has positive result on engine performance [24].

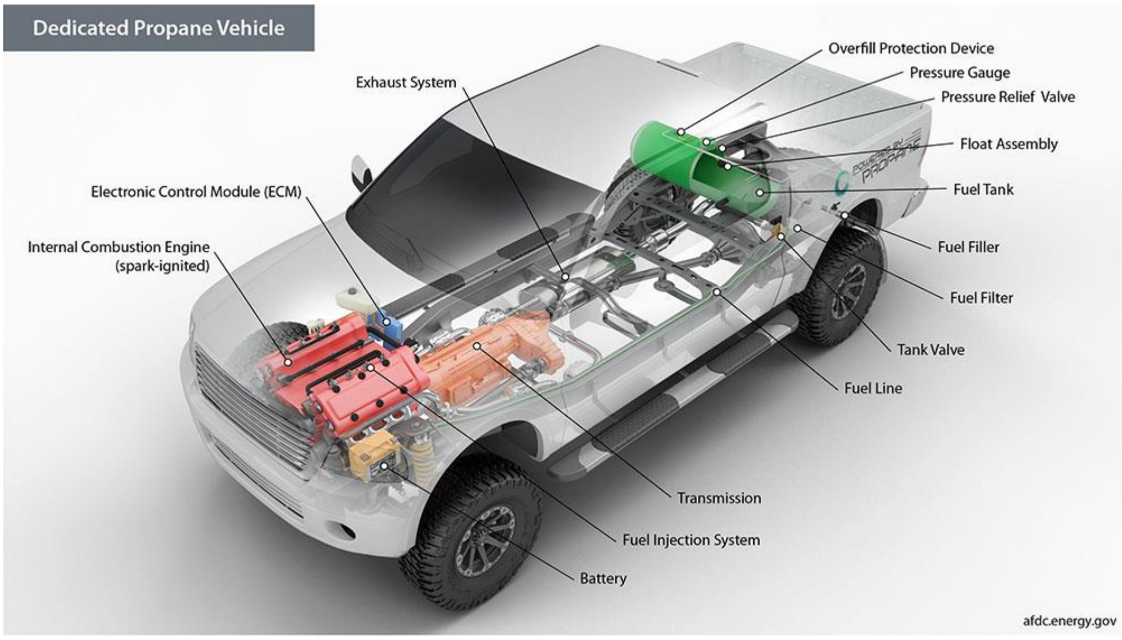

Figure 13. Dedicated LPG Vehicle [24].

2.2.2 BI-FUEL RETROFITTED LPG VEHICLE

Bi-fuel vehicles use classic spar-ignition engines able to run on either LPG or gasoline. The driver can easily select on which fuel he wants to run on by flipping the switch on the dashboard. The vehicle is equipped with fuel tanks, fuel injection systems and fuel line for both fuels. Bi-fuel vehicles can extend the range of the vehicle due to additional LPG tank. On the other hand the tank has to be stored in the boot, which means the car will have smaller boot capacity and will be heavier. LPG has higher octane number than gasoline, but in case of bi-fuel vehicles cannot be take the advantage of it, because the compression ratio has to be set to levels that gasoline requires [26].

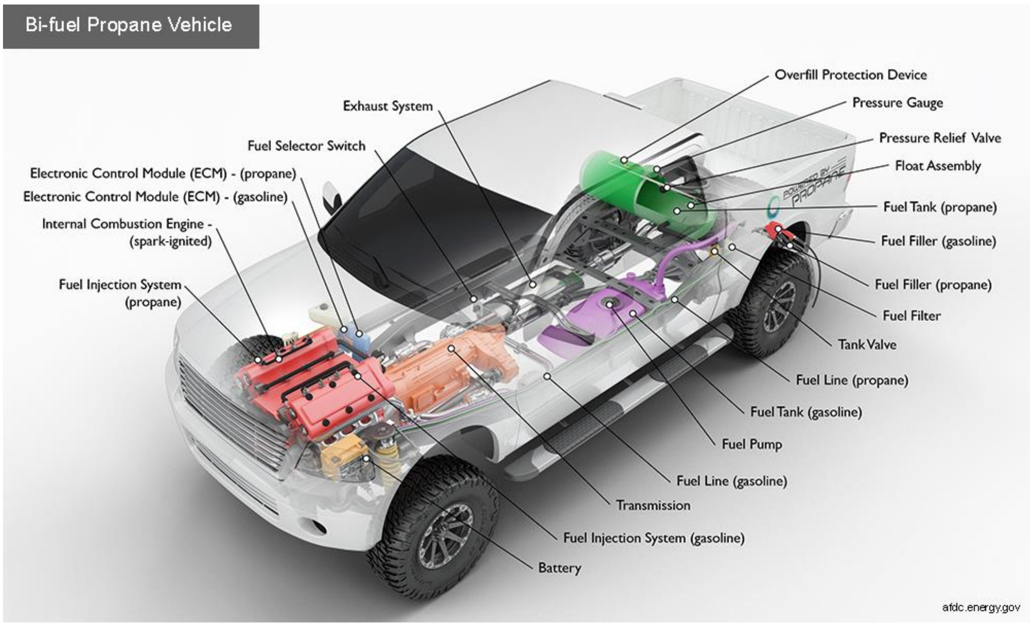

Figure 14. Bi-fuel LPG vehicle [25].

2.2.3 Costs

The average price of the conversion from gasoline to LPG bi-fuel is in Czech Republic approximately about €760-1,520. It depends on many specifications such as direct or port injection, number of cylinders and brand of the LPG kit. Most common is retrofitting the 4 - cylinder engine and that will cost around €1,085. In Czech Republic is the tax from LPG around 16 % [60], whereas from gasoline is 66 % and from diesel is 59 % [59].

Table 2.2: Average price of gasoline and LPG in selected states in EU to 6. March 2021 [27].

Country	Gasoline price [€/l]	LPG price [€/l]	LPG per litre gasoline equivalent [-]
Belgium	1.440	0.561	0.390
Czech Republic	1.177	0.510	0.433
Germany	1.511	0.677	0.448
Italy	1.657	0.654	0.395
Netherlands	1.780	0.723	0.406
Poland	1.086	0.539	0.496
Spain	1.337	0.704	0.527
Average	**1.427**	**0.624**	**0.442**

In case of LPG I took as an example the Dacia Duster. In Dacia configurator you can choose from two diesel, three gasoline and one bi-fuel engines. For these comparison I chose: 1.0 TCe 90 4x2 (74 kW) engine that runs on gasoline. Average fuel consumption given by manufacturer is 5.3 l/100 km. Now if we image the same distance that was used in CNG example – 15,000 km per year, the year cost will be about €936 (using the average gasoline price in Czech Republic from Table 2.2). As the other engine was chosen the 1.0 TCe 4x2 LPG engine which is bi-fuel engine able to run either gasoline or LPG. The average fuel consumption taken from Dacia's brochure is 6.8 l/100km [28]. With the same year load of 15,000 km per year will the year costs in Czech Republic make approximately €520. So the year saving is equal to €416, that is 44 % lower year costs compared to gasoline engine. Return of the beginning investment will be quicker as in case of CNG – within 3 years will be back.

2.2.4 Emissions

In the view of CO_2 emissions, the numbers from the brochure claims that the 1.0 TCe gasoline engine produces 121 g/km whereas the 1.0 TCe LPG engine running only on LPG produces 111 g/km [28]. The saving of the carbon dioxide emissions is small because LPG produces only 8 % fewer CO_2 emissions.

Faculty of Mechanical Engineering, University of Maribor took a look on LPG emissions coming from exhaust pipe. In these study was taken the 4-cylindre Opel converted into bi-fuel LPG vehicle and then were measured the emissions running on gasoline or LPG only. Because it is from 2011, the NEDC testing procedure was used. Total time of the test was 1,180 seconds – 780 seconds was urban cycle and 400 seconds was extra urban cycle [41]. The reduction of unwanted emissions were following:

- CO by 30 % in urban cycle and by 10 % of extra urban cycle,
- HC by 30 % in urban cycle and by 51 % of extra urban cycle,
- NO_x by 41 % in urban cycle and by 77 % of extra urban cycle,
- CO_2 by 10 % in urban cycle and by 11 % of extra urban cycle [41].

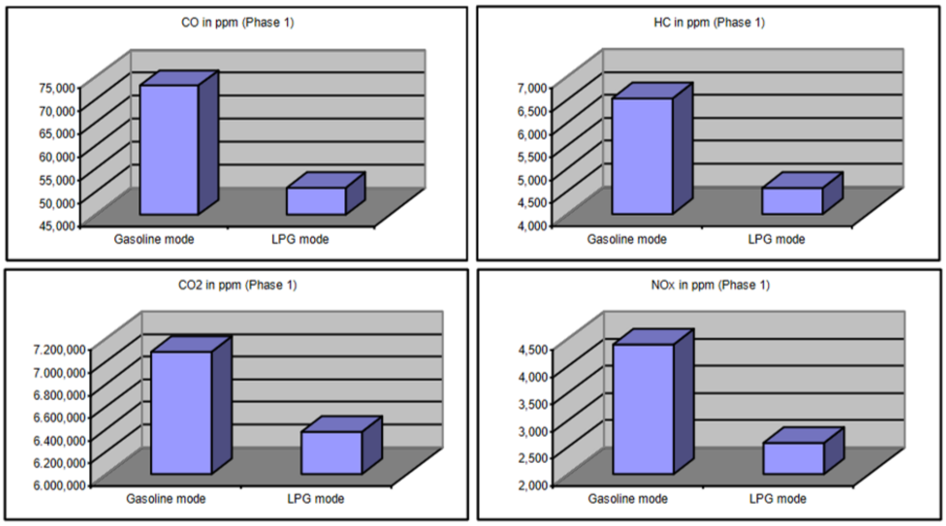

Figure 15. Emission comparison between gasoline and LPG mode in urban cycle (Phase 1) [41].

It was clearly proved, that conversion into bi-fuel LPG can lead to reduction of unwanted emissions. In case of popular CO_2 emissions can LPG save about 10.5 % of these emissions compared to gasoline.

2.2.5 ADVANTAGES OF LPG

+ **Lower overall running costs** – according to March 2021 the price of 1 litre of LPG is approximately 50 % lower than price of 1 litre of gasoline (Table 2.2.).
+ **Produce fewer unwanted emissions** – can lead to reduction of CO_2 about 10.5 % [41].
+ **Longer engine life** - LPG low carbon and low oil contamination extends life of the engine [26].

2.2.6 DISADVANTAGES OF LPG

- **Less space in boot and bigger weight** - LPG fuel tank situated in boot takes free space and also leads to increasing of weight of the vehicle.
- **Smaller network of LPG refuelling stations** – LPG refuelling stations is more than CNG, but it is still fewer than normal petrol stations (In Czech Republic there is 955 of LPG refuelling stations but 2,837 of classic petrol stations) [14].

2.3 ETHANOL (E85)

Ethanol (CH_3CH_2OH) is a clear, colourless liquid made from various plant materials known as biomass [32]. Ethanol is added in majority of all gasolines in the world and for example most gasoline sold in European Union contains 5 % of ethanol and 95 % of gasoline with label E5. Some of the countries have already introduced E10 (10 % of ethanol, 90 % of gasoline) like Belgium, Slovakia, Denmark, Finland etc. [31].

But ethanol can also be the majority in the blend which represents the common E85. It can be used in vehicles called “Flexible Fuel Vehicles (FFVs)”, vehicles with classic combustion engine capable to run on gasoline or blend of gasoline and ethanol. The ratio of ethanol can be various and depends on countries – in United States of America is the ratio between 51 - 83 % [32] of ethanol and in European Union it is between 65 % and 85 % [31]. Ethanol has lower energy value than gasoline around 27 MJ/kg, that means E85 has the energy value approximately around 30 MJ/kg, smaller than gasoline [34]. FFV vehicles have one fuel system and have basically the same fuel or engine components except to some ethanol-compatible components such as modification of fuel pump or fuel injection due to different chemical features and lower energy content of ethanol. The ECM (Electronic Control Module) needs to be also calibrated for usage of ethanol [33].

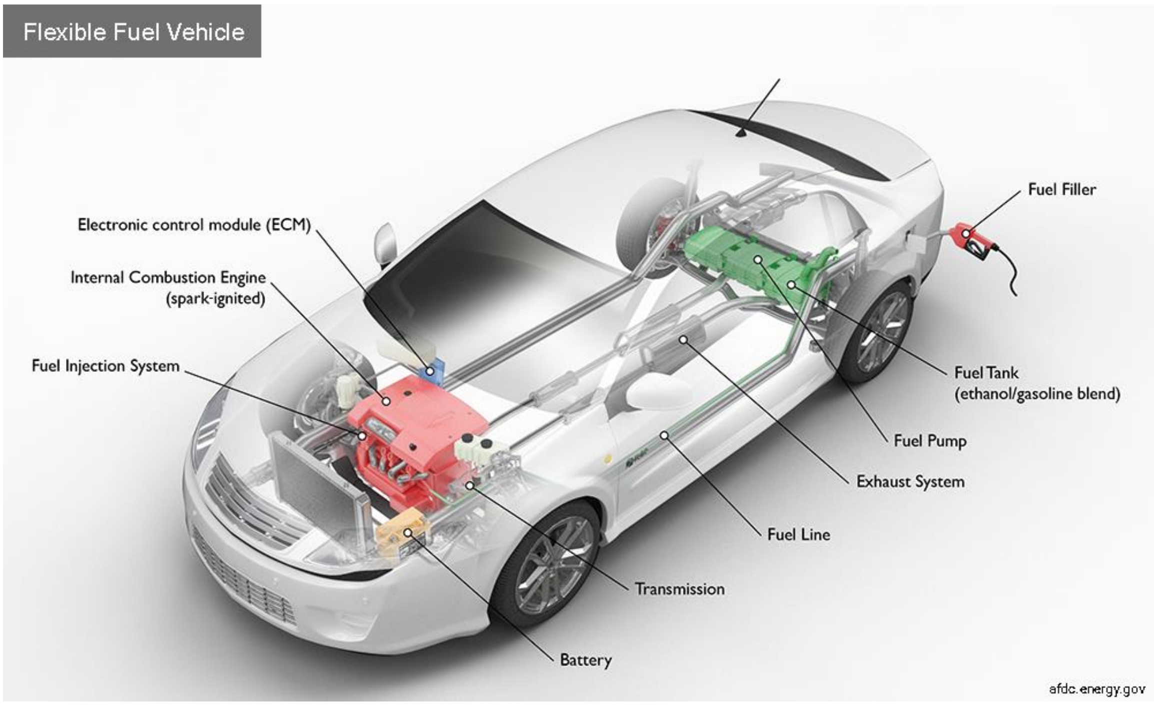

Figure 16. Flexible Fuel Vehicle running on ethanol [33].

2.3.1 Costs

The conversion of the vehicle to ethanol is not very popular in European Union but it is not as difficult as conversion into CNG or LPG. In Czech Republic the average price of conversion is approximately between €150-650. It depends on number of cylinders and brand of conversion kit. The most usual is conversion of a 4-cylindre engine and that costs around €320.

Table 2.3: Average price of gasoline and ethanol E85 in selected states in Europe to 8. March 2021 [35].

Country	Gasoline price [€/l]	E85 price [€/l]	E85 per litre gasoline equivalent [-]
Czech Republic	1.190	0.952	0.800
France	1.543	0.700	0.454
Spain	1.339	1.480	1.105
Sweden	1.430	1.100	0.769
Average	**1.376**	**1.058**	**0.782**

As an example of Flexible Fuel Vehicle (FFV) I chose 2020 Chevrolet Impala sold in United States of America with 3.6l V6 engine. The average fuel consumption of gasoline is 22 mpg. This needs to be convert into European l/100km – 1 MPG equals 235.215 l/100 km. This means that the fuel consumption is 10.7 l/100 km. If we take again as an example the 15,000 km per year, with prices from Czech Republic the year costs will reach €1,910. The average fuel consumption running on ethanol E85 only is 16 mpg, in European metrics 14.7 l/100 km. By the same road load of 15,000 km per year the costs in Czech Republic will reach €2,099. Which unfortunately shows that there are no cost savings due to bigger fuel consumption and not that convenient price of E85. The difference is only €189 per year, but the return of beginning investment will never be accomplished.

2.3.2 EMISSIONS

Institute of Energy and Transport under the European Commission issued a study with precise details about flex-fuel light duty vehicles. They took to cars – named "Vehicle 1" (V1) with direct fuel injection and "Vehicle 2" (V2) with port fuel injection. The NEDC testing procedure was used and as a E5 fuel is considered the standard gasoline [42].

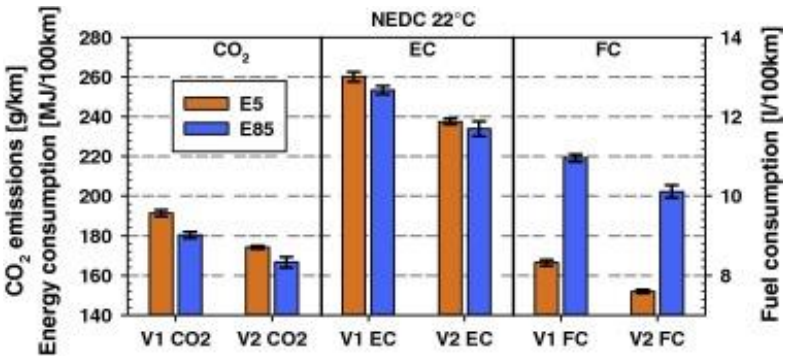

Figure 17. CO_2, Energy consumption (EC) and fuel consumption (FC) average values over NEDC for the vehicles tested with E5 and E85 fuels [42].

These study has shown that the conversion on E85 fuel will save 5.7 % of CO_2 emission in case of Vehicle 1 and 4.3 % of CO_2 emissions in case of Vehicle 2. If we make an average of it, E85 fuel can save around 5 % of CO_2 emissions. In case of hydrocarbons (HC) there is not significant reduction and the NO_x emissions has slightly decreased by Vehicle 1 but raised by Vehicle 2 [42].

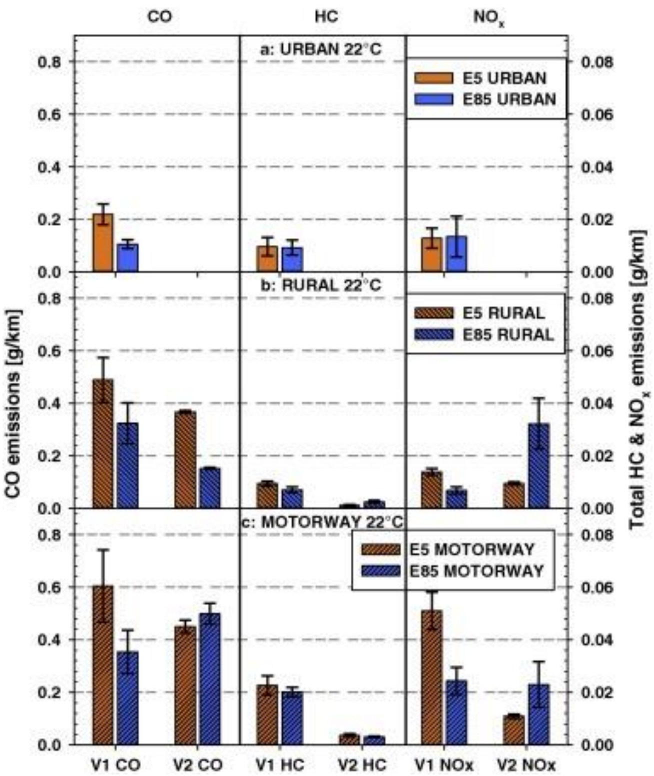

Figure 18. CO, total HC and NO_x average emission values over the Common Artemis Driving Cycle (a) urban, (b) rural and (c) motorway for the vehicles tested with E5 and E85 fuels [42].

2.3.3 ADVANTAGES OF E85

+ **Lower overall running costs** – according to March 2021 the price of 1 litre of E85 is approximately 23 % lower than price of 1 litre of gasoline (Table 2.3.).
+ **Produce fewer unwanted emissions** – can lead to reduction of CO_2 about 5 %.

2.3.4 DISADVANTAGES OF E85

– **Bigger fuel consumption** – fuel consumption raise about 27 % which leads into financial disadvantage because running on E85 is more expansive than gasoline
– **No return of beginning investment** – because is more expensive to run on E85 therefor the return investment will never be accomplished.

2.4 WATER INJECTION

Water injection is a quite old property. It was used before Second World War as an experiment in aeroplanes and bombers for short-term increasing of power of a jet engine. After decades this idea was taken and put into passenger cars. First was in 1962 the Oldsmobile F-85 Jetfire, than for example in 1980’s the Saab 99 Turbo and recent popular use was in 2016 BMW M4 GTS [44].

Water injection works on basis, that the precisely amount of distilled water is injected into combustion chamber, where is the water vaporized. That results into cooling the fuel mixture – the mixture now has lower volume, so it is possible to get bigger amount of fuel mixture into combustion chamber, but the other result is lower temperature of the fuel mixture which means that is possible to increase the compression ratio and that results into more efficiency combustion as well as increasing of power [45]. The usage of water is so convenient because of water's latent heat of vaporization – 2,257 kJ/kg. In comparison with gasoline mixture which has between 350-400 kJ/kg [46]. Other advantage of water is that is easily affordable.

Normal combustion engine waste around 20 % of the fuel they consume for cooling down the engine instead of propulsion, especially in higher speeds, where is the cooling more necessary. Bosch company came up with modern port water injection system, that should solve this problem by cooling down the engine by injected water [48]. Their water injection system can reduce fuel consumption by 13 % in rapid accelerations or higher speeds at highways and around 4 % in normal driving (WLTC) [47]. Other benefit of Bosch water injection system is boost of horsepower around 5 %. Fitted additional 5l water tank will last for approximately 3,000 km, because it uses only few millilitres for every 100 km of driving. There is no need to worry about rust because every bit of water evaporates before the actual combustion happens and when the water tank runs dry, the car can easily carry on as normal. According to Bosch, their water injection system can reduce unwanted CO_2 emissions about 4 % [49].

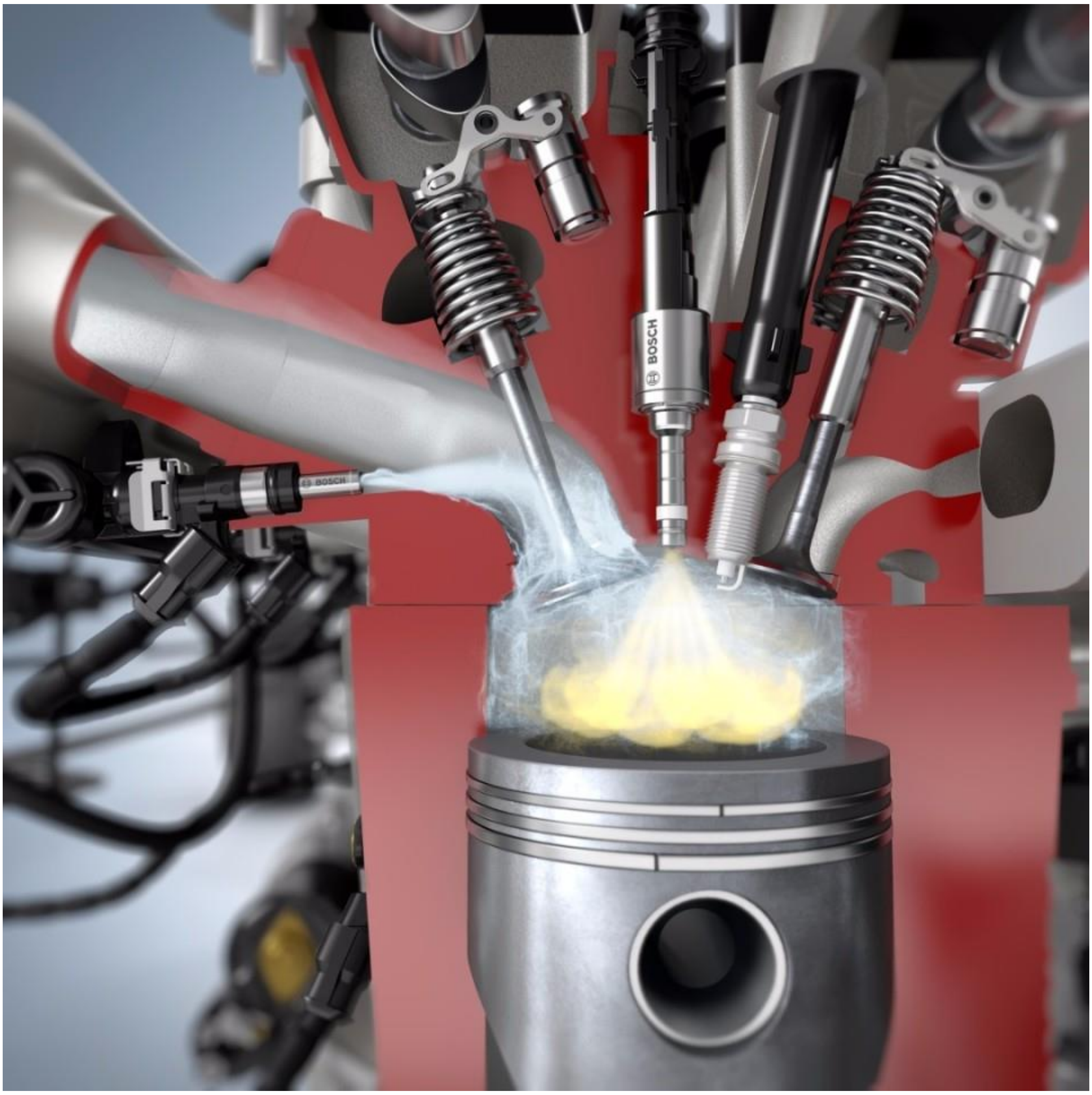

Figure 19. Bosch water injection system [49].

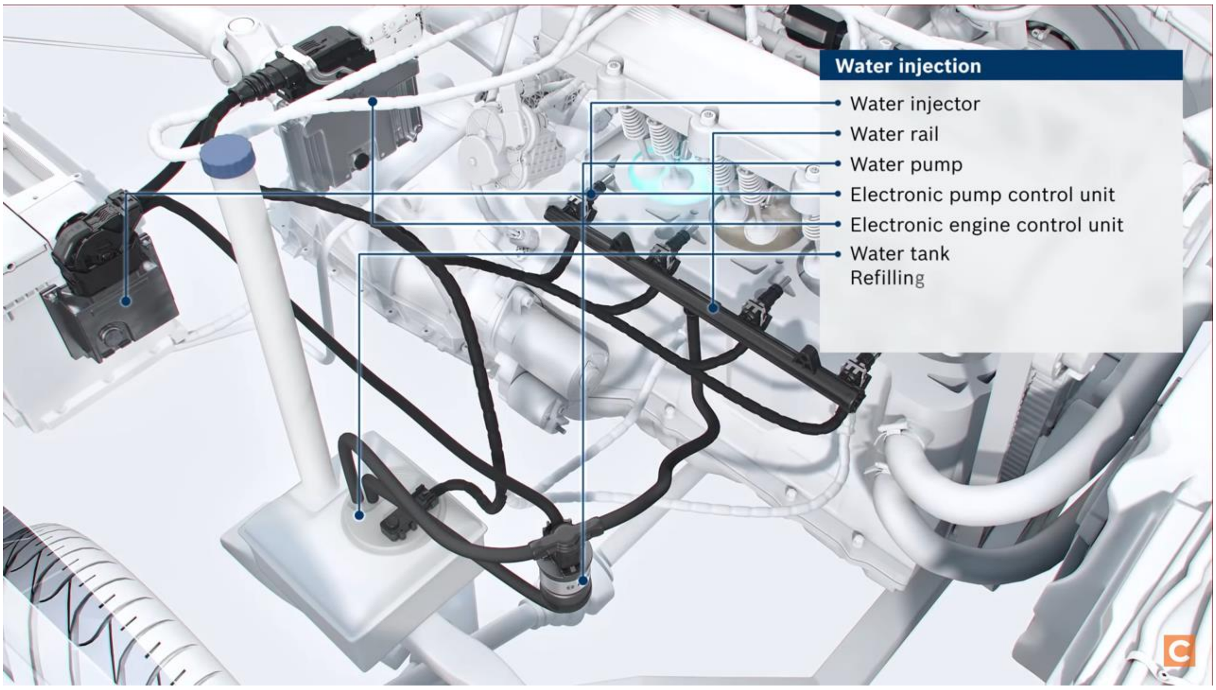

Figure 20. Components of Bosch water injection system [50].

2.4.1 Costs

Additional fitting of an vehicle with water injection system is not in use as a kit yet.

2.4.2 Emissions

One of the latest studies from Institute of Automotive Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University was dealing with port water injection and its effect on combustion and emissions in spark ignition direct injection engine. The study used inline-three-cylinder engine equipped with turbocharger and with charge air cooler [51].

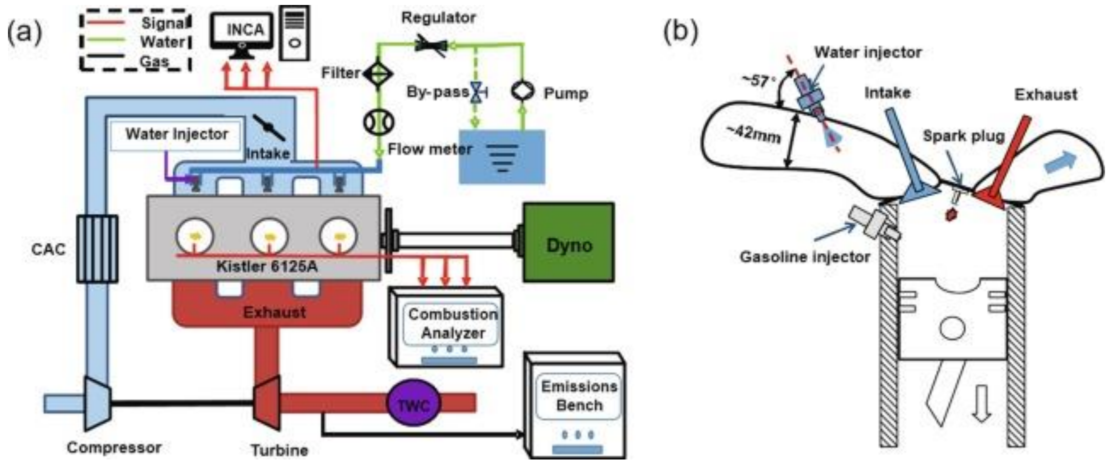

Figure 21. Experimental schematics for the port water injection method. (a) Engine bench setup, (b) Water injector installation scheme and dimensions [51].

In this investigation was used four types of engine conditions:

- Condition (1) (1,500 RPM and 170 Nm) represents low speed, high load conditions,
- Condition (2) (5,200 RPM and 150 Nm) represents high speed, full load conditions,
- Condition (3) (5,200 RPM and 150 Nm) represents high speed, full load conditions,
- Condition (4) (2,800 RPM and 95 Nm) represents medium speed, part-load conditions [51].

Conditions (2) and (3) are not exactly the same – Condition (2) fixed the excess air ratio λ to 0.86 whereas under Condition (3) the exhaust temperature is limited to 930 °C but with variable excess air ratios [51].

NO_x emissions, particle number (PN) count, total hydrocarbon (THC) and CO emissions were measured in the area of “effect of water injection on the emissions”. NO_x emissions decreased in cases (1), (2), (4) with fixed excess air ratio λ, because the port water injection caused lowering the temperature in the cylinder and therefore lowering the amount of NO_x emissions. Whereas in Condition (3) the in-cylinder temperature remained basically unchanged, so under these conditions it was the concentration of oxygen that effected the NO_x emissions and that is the reason for the substantially increase of NO_x emissions. It needs to be noted that the NO_x measurement was used before three-way catalyst. That explains that the tailpipe NO_x emissions will be lower in practical applications [51].

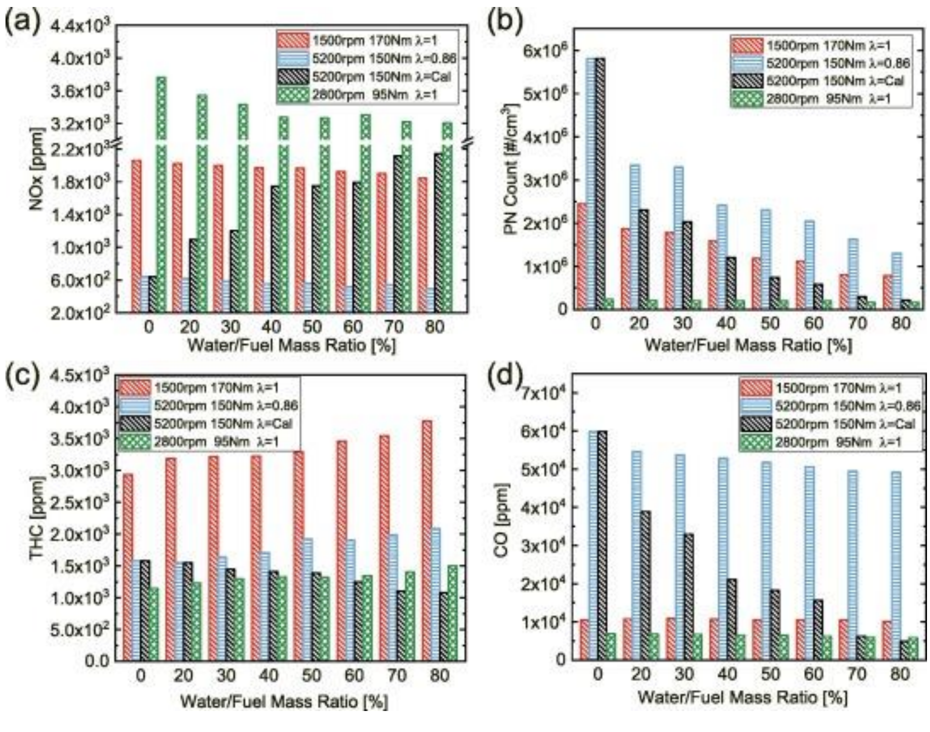

Figure 22. Combustion emission investigation under the four conditions – (a) NO_x emission, (b) PN count, (c) THC emission and (d) CO emission [51].

PN count was reduced under all four conditions with increasing of water/fuel mass ratio. In case of THC emissions, when the water injection dropped the in-cylinder temperature, the THC emissions increased. Only reduce of THC emissions was under Condition (3) caused high in-cylinder temperature and lower combustion equivalence ratio. The reduction of CO emission is less significant under Condition (1) and (4), but is more visible under high load conditions [51].

The result of this study corresponds with other existing literature - that means increasing of THC whereas the NOx, PN and CO emissions were reduced. That leads to conclusion that the water injection due to lowering the in-cylinder temperature and fuel enrichment elimination can reduce unwanted emissions [51].

2.4.3 ADVANTAGE OF WATER INJECTION

- **More horsepower** - according to Bosch, water injection system can lead to increasing of power around 5 % [49].
- **Lower fuel consumption** – fuel consumption should be lower by 13 % in high speeds or rapid accelerations and around 4 % lower in normal driving regime [47].
- **Lower emissions –** according to Bosch water injection system can reduce CO_2 emissions by 4 % [49].

2.4.4 DISADVANTAGES OF WATER INJECTION

- **It is not used in larger scale** – water injection is here for nearly 80 years but in these days only BMW M4 GTS from modern passenger cars is equipped with water injection system.
- **Additional water tank and other components** – the engine needs to be equipped with water injection components and the ECU needs to be programmed.

2.5 HYDROGEN

Using hydrogen as a fuel is one of the biggest hopes for the future of vehicle transport, because it is a fuel with ability to reduce air pollution. Only problem with hydrogen is its obtaining because it is difficult to separate hydrogen from natural compounds. On the market are vehicles e.g. Toyota Mirai with fuel cells that uses hydrogen for producing electricity that subsequently powers the vehicle. But there is another example of using hydrogen in vehicles and that is combination of hydrogen with petroleum-derived fuels in internal combustion engines. These combination can also lead to reduction of harmful emissions from fossil fuels. Calorific value of hydrogen is 119.9 MJ/kg which is more than twice more comparing to gasoline 44.5 MJ/kg. Hydrogen also has higher auto-ignition temperature 585 °C than gasoline (260-460 °C) or methane (360-540 °C). Common problems with hydrogen used in internal combustion engines are – compression ratio, temperature, back-ignition, early ignition and knocking [54].

Hydrogen internal combustion engine (HICE) vehicles are not as clean as we think, even though there is no carbon in combustion process, it still produces nitrogen oxide emissions. Other big problem with HICE vehicles is their efficiency. Only 25 % of the hydrogen’s potential energy is transferred to wheels compared to 50 % in case of hydrogen fuel cells. Hydrogen also needs to be stored in big tanks which takes a lot of space, so manufacturing hydrogen fuel cell vehicles makes more sense than vehicles with hydrogen internal combustion engines because they need smaller tanks and have 25 % more efficiency [62].

As a hydrogen internal combustion vehicle was in 2006 introduced prototype BMW Hydrogen 7 but it never get in serial production.

Figure 23. BMW Hydrogen 7 [52].

2.5.1 Costs

Conversion of gasoline engine vehicle on hydrogen internal combustion engine (HICE) vehicle is complicated, has lower efficiency than hydrogen fuel cells and needs bigger hydrogen tanks and that are the main reasons, that HICE vehicles did never get into bigger serial production. And there is no conversion kit for hydrogen available on the market.

2.5.2 Emissions

Result of combustion of hydrogen is only water, with high combustion temperatures the NO_x emission occurs due nitrogen and oxygen in the air. CO, CO_2 or HC emissions should not exist, because there is no carbon in structure of hydrogen, but due to combustion of the lubricating oil on the surfaces in cylinder minimum amount of CO, CO_2 or HC will occur [54].

2.5.3 Advantages of hydrogen

- **Minimum emission fuel** – hydrogen as a fuel can reduce carbon emissions to absolute minimum, in case of hydrogen fuel cells it is zero emission.
- **Hydrogen as a unlimited source of energy –** even if it is still difficult to obtain basic hydrogen from natural compounds, for the future it is unlimited source of energy in contrast to petroleum-derived fuels.

2.5.4 Disadvantages of hydrogen

- **Small efficiency** – one of the main reasons why the HICE vehicles never get into serial production is their small efficiency (25 %) compared to hydrogen fuel cells with 50 % [62].
- **Back-ignition, knocking and early ignition** – problems that will occur when engine is converted into hydrogen internal combustion engine.

- **Big hydrogen fuel tanks** – big fuel tanks needs to be installed into car which takes space and add weight.
- **Minimum network of hydrogen fuel stations** – for example in Czech Republic there is only one non-public hydrogen fuel station and first three are in building-up [53].

2.6 COMPARISON

Table 2.6 contains summary of all fuels physical properties.

Table 2.6. Physical properties of fuels [54].

Fuel	Calorific value [MJ/kg]	Air fuel mixture ratio [-]	Flame temperature [°C]	Auto-ignition temperature [°C]
Gasoline	44.5	14.6	2,307	260-460
Diesel	42.5	14.5	2,327	180-320
Methane	50	17.2	1,914	360-540
Propane	45.6	15.6	1,925	450
Ethanol	30 [34]	9.75 [64]	1,920 [65]	363 [66]
Hydrogen	119.9	34.3	2,207	585

Table 2.7. Average economical aspects of selected retrofits.

Fuel	Average price of conversion [€]	Average saving per year [€]	Average return of beginning investment [years]	Average reducing of CO2 emission [%]
CNG	1,550	374	4.14	32
LPG	1,085	416	2.61	10.5
E85	320	-189	∞	5

Economical aspects from Table 2.7 are taken on different types of vehicles but all with the same road load of 15,000 km per year and they are calculated with prices in Czech Republic.

3 STATISTICS OF PASSENGER VEHICLES IN USE IN THE EUROPEAN UNION

In 2019 there was 242,727,242 passenger cars in use on roads in the European Union. That is 1.8 % more than in year 2018 and 7.6 % more than in 2015. The average age of vehicles in EU is 11.5 years old. Despite the recent increasing interest and sales, alternatively-powered vehicles make up only 4.5 % of total European fleet. There are 52.9 % gasoline, 42.3 % diesel vehicles. Alternative fuel cars takes only 3.2 % with 0.5 % CNG and 2.7 % LPG. Battery electric, hybrid electric and plug-in hybrid vehicles make up only 1.2 %. There are also 0.1 % vehicles running on other fuels and 0.2 % is unknown [55].

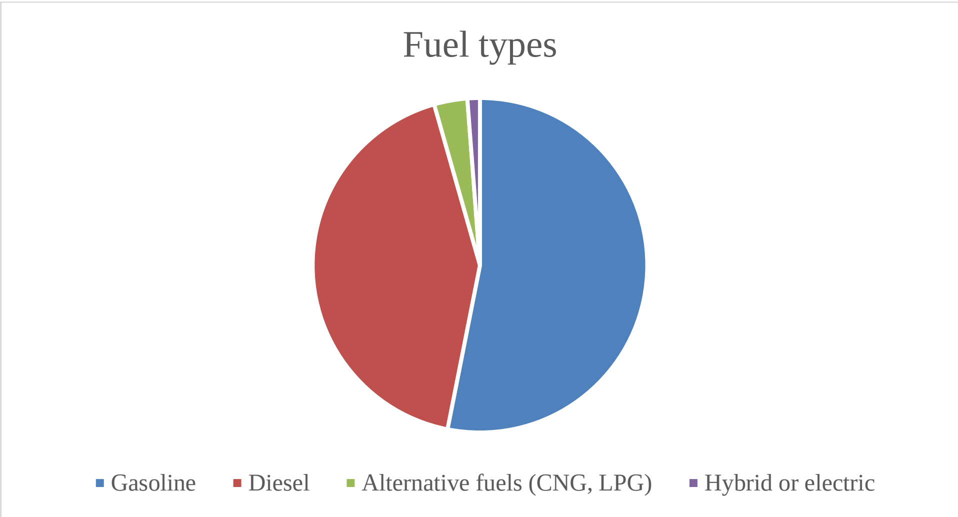

Figure 24. Total European fleet – vehicle in use, by fuel type.

According to the International Council for Clean Transport there was about 15.5 million new cars registrations in the EU in 2019. About 60 % of them were Euro 6d-TEMP compliant. Average CO_2 emissions for all new registered cars in the European Union were 122 g/km in 2019 [56].

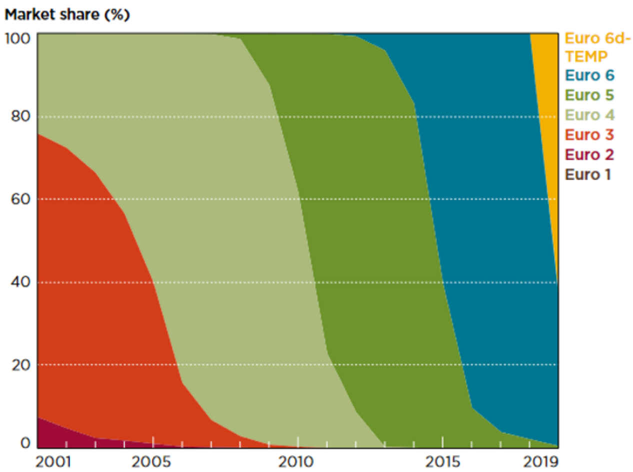

Figure 25. Passenger cars: Market share by emission standard [56].

In general there are around 12.4 million cars in use on roads in the EU that has been made in 2019 which means that they are Euro 6d-TEMP compliant. About 46.5 million passenger cars are still Euro 6 compliant (6b or 6c). Euro 5 (5a or 5b) vehicles, which means they were built between 2011-2014, are around 38.6 million. And more than 143.7 million of a European passenger cars are Euro 4 or even older Euro compliant [55].

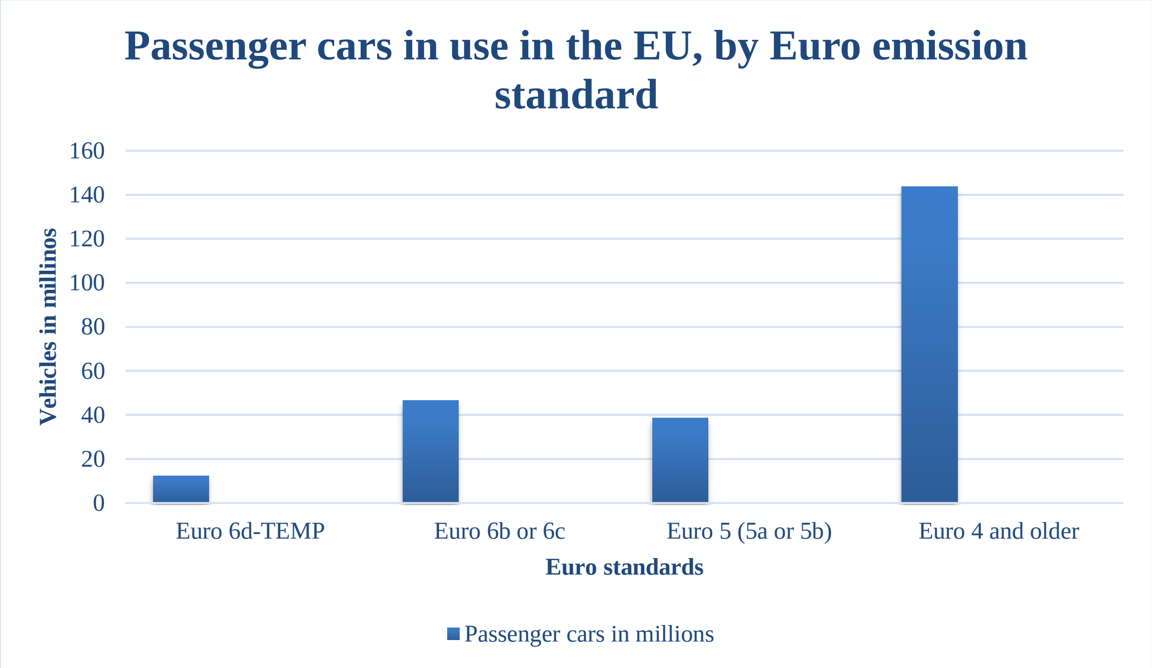

Figure 26. Passenger cars in use in the EU, by Euro emission standard.

The CO_2 emissions coming from exhaust pipe of a Euro 6d-TEMP compliant vehicles was 122.4 g/km [57]. In 2020 it should be under 120 g/km and in 2021 the maximum limit was set to 95 g/km [21]. The average carbon dioxide emissions from passenger cars made between 2000 and 2010 are 160 g/km, from passenger vehicles made between 2010 and 2018 it is 124.4 g/km. From that we can assume that the average carbon dioxide emissions coming from exhaust of a vehicles in use made between 2000-2018, which means not Euro 6d-TEMP or Euro 6d compliant cars, are 142.2 g/km [57].

But CO_2 emissions are produced not only during driving of already made car, the CO_2 emissions are also produced during manufacturing of that particular vehicle and also during manufacturing of the fuel, in these case - gasoline. That clearly shows Figure 27, where is illustrated how much grams of CO_2 emission per kilometre needs to be considered in whole vehicle lifetime assuming 220,000 km mileage.

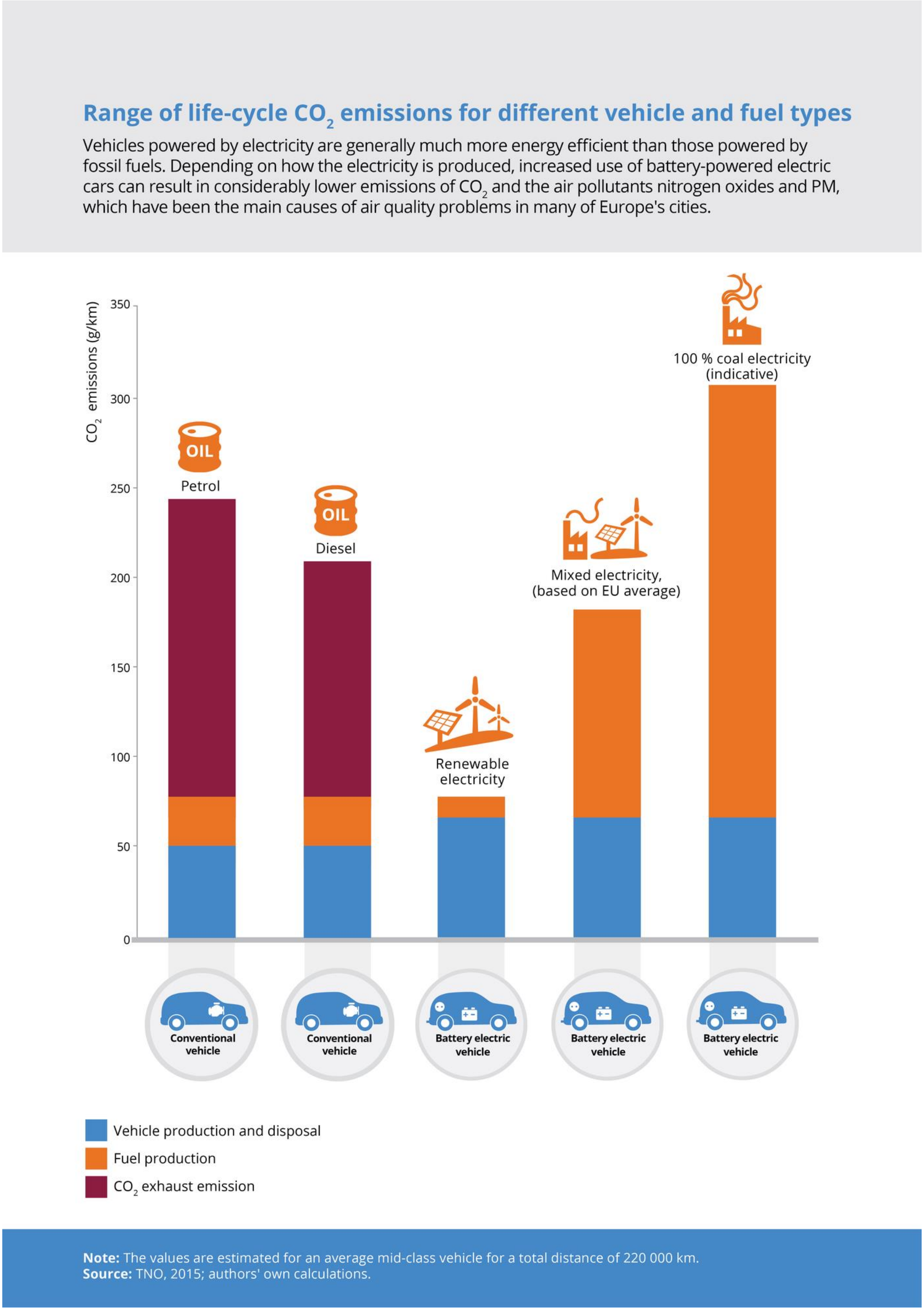

Figure 27. Range of life-cycle CO2 emissions for different vehicle and fuel types from 2015 [58].

In example will be shown a future environmental burden of a new gasoline Euro 6d vehicle compared with an older already produced vehicle, equipped with different retrofits. In example it is considered, that the vehicle will make 20,000 km per year and ends its lifetime after 11 years with 220,000 km, as it is showed in Figure 27.

If we consider that making of a vehicle and its disposal costs additional 50 g/km [58] of CO_2 emissions during the whole 220,000 km lifetime's cycle – that means that only making gasoline Euro 6d vehicle is responsible for 11 tonnes of CO_2. And if that car will produce approximately 95 g/km CO_2 emissions as it should from January 2021 [21], it will result to producing another 20.9 tonnes of CO_2 emissions during the whole lifetime cycle with 220,000 km at the end.

In my example, I will compare two possibilities:

1. Making and using brand new Euro 6d gasoline vehicle for 11 years with 20,000 kilometres per year
2. Using older gasoline vehicle, that is equipped with retrofit to reduce CO_2 emissions, for the same 11 years with 20,000 kilometres per year

And I will explore which of these two possibilities have bigger impact on environment and which of these two solutions will produce after these 11 years of usage bigger amount of CO_2 emissions in total.

In case of already produced gasoline vehicles, I assume average 142.2 g/km of CO_2 emissions per vehicle, which is average of averages of CO_2 emissions produced by vehicle between 2000-2018 [57]. Then I took the percentage reduction of CO_2 emissions taken from attached studies and researchers in case of every retrofit. For CNG I chose 32 % reduction which is average of results from studies [12] and [63]. In case of LPG I chose 10.5 % reduction – that is average of results from study [41]. For E85 it is also the average of results from study [42]. And in case of water injection I took the 4 % reduction according to Bosch [49]. All it is shown in these Table 3.1. The conversion of gasoline vehicle into hydrogen was not considered, because it never get into serial production and any kit for conversion is not available at the market.

Table 3.1 Retrofits and their percentage reduction.

Retrofit	Reduction [%]	CO_2 emissions without retrofit [g/km]	CO_2 emissions with retrofit [g/km]
CNG	32	142.2	96.7
LPG	10.5	142.2	127.3
E85	5	142.2	135.1
Water injection	4	142.2	136.5

In Figure 28 needs to be noted, that was not considered how much CO_2 emissions are produced during making CNG, LPG or E85 as a fuel or how much CO_2 emissions are produced during manufacturing of the necessary components for these retrofits.

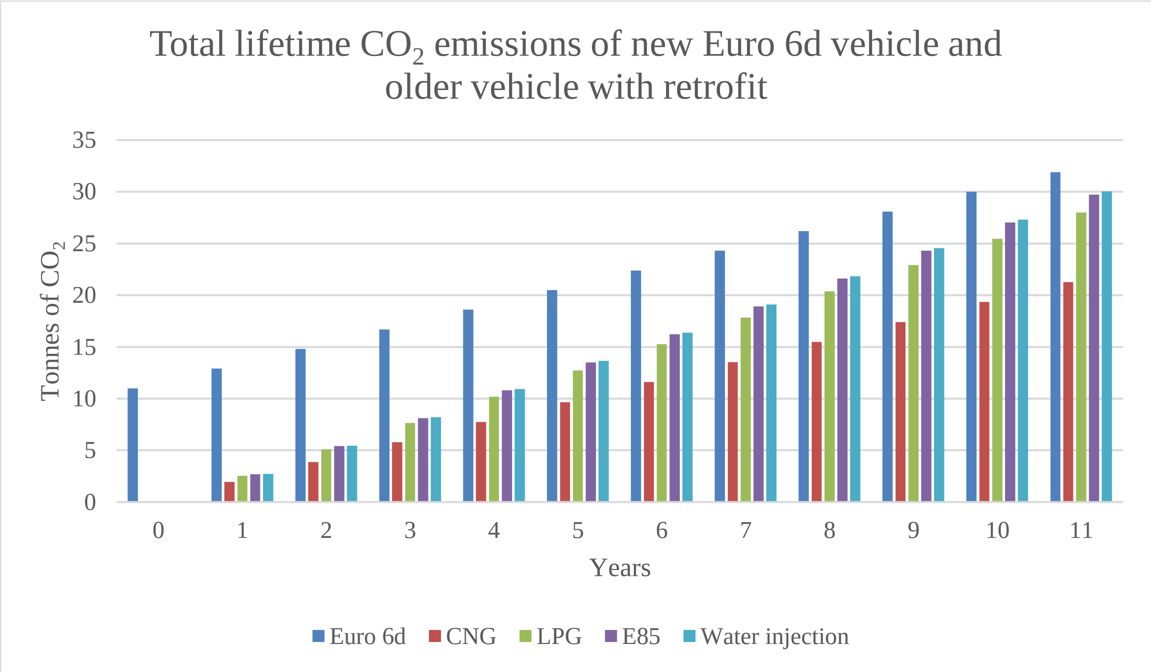

Figure 28. Lifetime CO_2 emissions of new Euro 6d vehicle and older vehicle with retrofit.

Figure 28 shows, that the making whole new vehicle, which is Euro 6d compliant, is in the first years disadvantageous because it starts with 11 tonnes of CO_2 emissions burden, because the whole new car needs to be made. On the other hand older vehicles do not start at 11 tonnes of additional CO_2 emissions, because the car is already made. And using numbers from Table 3.1. it is clear, that the best retrofit for CO_2 reduction is CNG.

In the end of 220,000 km life-cycle the total CO_2 emissions are:

- 31.90 tonnes of CO_2 emission for Euro 6d gasoline vehicle,
- 21.27 tonnes of CO_2 emission for already produced gasoline vehicle with CNG,
- 28.01 tonnes of CO_2 emission for already produced gasoline vehicle with LPG,
- 29.72 tonnes of CO_2 emission for already produced gasoline vehicle with E85,
- 30.03 tonnes of CO_2 emission for already produced gasoline vehicle with water injection.

From Figure 28 we can see that every retrofit is more convenient than buying a new car in the area of environmental burden, but again needs to be noted, that retrofits will not start from zero, because some CO_2 emissions are produced during manufacturing these retrofits.

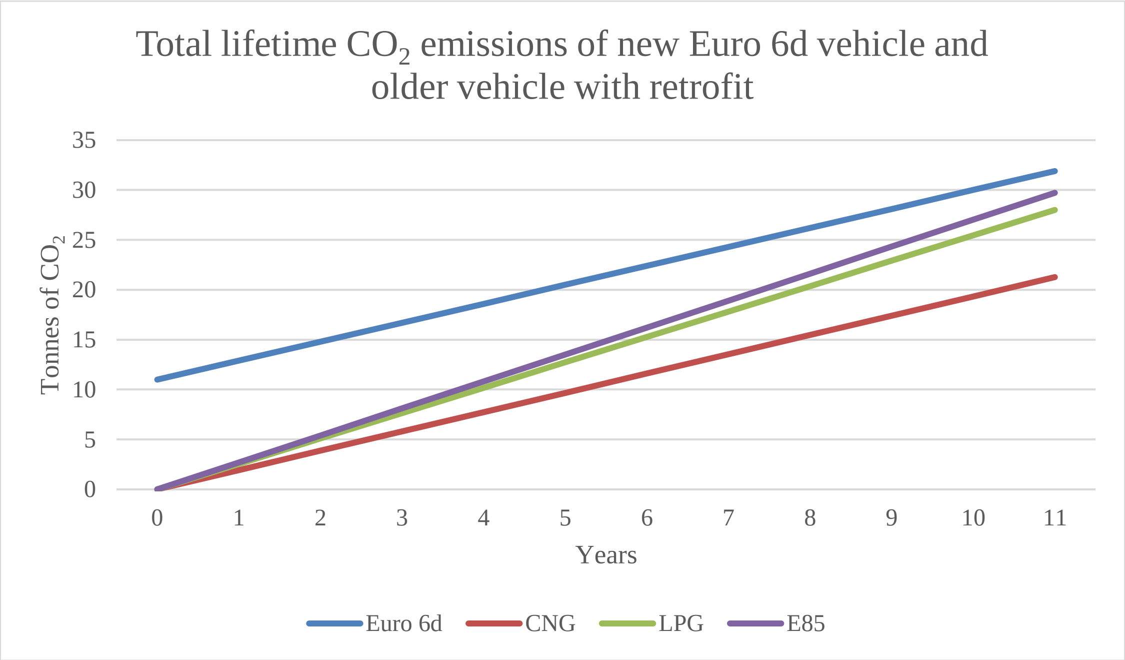

Figure 29. Lifetime CO_2 emissions of new Euro 6d vehicle and older vehicle with retrofit.

In Figure 29 is used the same data as in Figure 28, except of water injection, because it has approximately the same values as E85. And it shows that the E85 and LPG will meet in a few years with the Euro 6d curve and start to be disadvantageous compared to new gasoline Euro 6d vehicle. From my calculations the E85 start to be disadvantageous after 13 years (260,000 km) and LPG after 16 years (320,000 km). The CNG will meet the Euro 6d curve after a non-realistic long period. Again we need to consider, that the meet of the Euro 6d curve will probably happen sooner, because of CO_2 emissions produced during manufacturing these retrofits and fuels, that are not considered in these calculation.

As an interestingness at Figure 30 I have added a comparison of new generation of gasoline vehicles with battery electric vehicle. In these case I assume the same road load of 220,000 km with 20,000 km per year. For these calculations I have used the approximately estimation form Figure 27. Estimated values of CO_2 emissions used for these comparison are:

- For **Euro 6d gasoline vehicle** – 50 g/km for vehicle production and disposal, 27.4 g/km for fuel production and 95 g/km for CO_2 emission from exhaust in usage,
- For **Euro 6d-TEMP gasoline vehicle** - 50 g/km for vehicle production and disposal, 27.4 g/km for fuel production and 120 g/km for CO_2 emission from exhaust in usage
- For **battery electric vehicle** – 66,1 g/km for vehicle production and disposal, 115,5 g/km for fuel production and 0 g/km for CO_2 emission from exhaust in usage [58].

In case of battery electric vehicle I used calculation of Mixed electricity based on EU average.

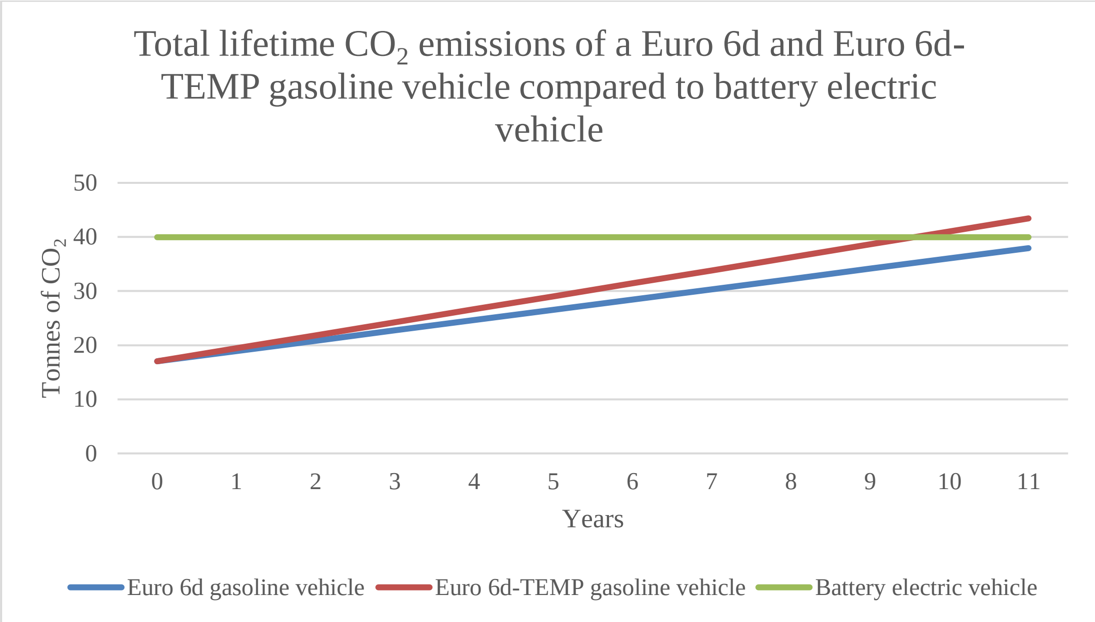

Figure 30. Total lifetime CO_2 emissions of a Euro 6d and Euro 6d-TEMP gasoline vehicle compared to battery electric vehicle.

We can see that the manufacturing of battery electric vehicle produce more CO_2 emissions than gasoline vehicle, probably due to batteries. And the huge difference is in case of fuel production, because there are still a lot of electricity that is produced in thermal power plants and they are big burden for the environment.

From Figure 30 we can approximately assume that the battery electric vehicle starts to be convenient for environment after 9.5 years of usage, approximately 190,000 km than a new gasoline vehicle made in 2020 that are Euro 6d-TEMP compliant. And in case of gasoline Euro 6d vehicle, if they will be able to accomplished limits set on 95 g/km of CO_2 emissions by EU for 2021, it will result at the end into approximately the same environmental burden that battery electric vehicle will made. Euro 6d gasoline vehicle will get even slightly better.

It needs to be noted, that there is an ecological progress in manufacturing of new vehicles, so production of a whole new car (gasoline or battery electric) in 2021 produces slightly less CO_2 emissions, than in my calculations.

If we take as a fact that there are 242.7 million of passenger vehicles in the European Union and 52.9 % of them are with gasoline engines. That is approximately 144.3 million vehicles. If we imagine that all European gasoline vehicles will get a donation from EU to buy an CNG conversion kit and everybody will actually do it. With approximately 32 % of reduction of CO_2 emissions in case of CNG, we will assume the difference between 142.2 g/km per gasoline vehicle and 96.7 g/km per vehicle with CNG kit. With 20,000 km per year, the year saving of CO_2 emissions will be approximately around 910 kg of CO_2 per vehicle. In these enormous theoretical scale, the year saving will be around 131.3 million tonnes of CO_2 per year, if every vehicle is equipped with CNG conversion kit.

CONCLUSION

Fight against unwanted emissions, especially CO_2, which causes air pollution will continue for years and years. There are 242.7 million passenger vehicles in use in the European Union, but only slightly more than 5 % of them are Euro 6d-TEMP or Euro 6d compliant. And making these new cars with better CO_2 g/km range, than the older one, produces also big amount of CO_2 emissions, because a new car needs to be made. Instead of that, we can equipped already produced vehicles with retrofits that are able to reduce the unwanted emissions coming from exhaust pipe. The basic retrofits that I chose were CNG, LPG, E85 ethanol, water injection and hydrogen.

Compressed natural gas, known as CNG, is with all of these calculations the best retrofit from selected ones. One of its biggest advantages is, that it is possible to reduce CO_2 emissions around 32 % and the other advantage is, that is financial convenient (after 4 years). Only few negative things are associated with CNG and that is you need to add in your car additional tank for CNG, which takes space and add some weight, and also not so big fuel stations network compared to gasoline or diesel.

Liquified petroleum gas, LPG, has approximately the same properties as CNG, but it cannot so effective reduce the CO_2 emissions (only 10.5 %). LPG needs the same features like CNG (additional tank, fuel injection etc.) but makes a slightly bigger costs saving per year than CNG.

Ethanol, most common as E85, is not in usage like CNG or LPG. It is mainly because in these days it is not financial convenient. The E85 fuel is cheaper than gasoline, but the fuel consumption increases about 27 %. That causes that you will never get back your beginning investment for conversion of your car form gasoline to E85 fuel. Also the CO_2 reduction is not that effective (around 5 %).

Water injection is here for nearly 80 years but it has never been used for decreasing of CO_2 emissions. In 2016 the BMW fitted the Bosch water injection system into their BMW M4 GTS. And they are claiming that the water injection system added more horsepower and also helped reduce fuel consumption and producing of CO_2 emissions. But it is a technology that has never been used in bigger scale. Also reduction of CO_2 by 4 % is not as good as in case of CNG.

Hydrogen is maybe the fuel of the future. But it will be the way with hydrogen fuel cells, that used hydrogen to produce electricity that powers the vehicle. Transforming of normal combustion engine into hydrogen combustion engine makes less sense in case of low effectivity. These cars will also need big fuel tanks to be able provide according driving range. And that will be the main reasons why these engines never get into serial production and always ended in prototypes, like in BMW Hydrogen 7.

To sum up my bachelor thesis I have found out, that the best retrofit for use in already produced passenger cars is CNG. My theoretical calculations are approximated and cannot be used as a facts. In calculations are not considered how much CO_2 emissions are produced during manufacturing of that particular fuel and also there is not considered how much CO_2 emissions is produced during manufacturing of these retrofits and components for these retrofits. But if there will be an EU donation program for people to buy an CNG kit for their vehicles, it can reduce the global CO_2 emissions significantly.

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LIST OF ABBREVIATED TERMS

λ	[-]	Excess air ratio
CH_3CH_2OH	[-]	Ethanol
CH_4	[-]	Methane
CNG	[-]	Compressed Natural Gas
CO	[-]	Carbon monoxide
CO_2	[-]	Carbon dioxide
E85	[-]	Blend of ethanol and gasoline
ECM	[-]	Electronic Control Module
ECU	[-]	Electronic Control Unit
EEA	[-]	European Economic Area
FFV	[-]	Flexible Fuel Vehicle
HC	[-]	Hydrocarbons
HICE	[-]	Hydrogen Internal Combustion Engine
LCV	[-]	Light Commercial Vehicle
LPG	[-]	Liquefied Petroleum Gas
NEDC	[-]	New European Driving Cycle
NMOG	[-]	Non-Methane Organic Gases
NMHC	[-]	Non-Methane Hydrocarbons
NO_x	[-]	Nitrogen oxide
PM	[-]	Particular Matter
PN	[-]	Particular Numbers
RDE	[-]	Real Driving Emissions
THC	[-]	Total Hydrocarbon Content
WLTC	[-]	World new Light vehicles Test Cycle
WLTP	[-]	World new Light vehicles Test Procedure