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Comparative Analysis on the Performance and Exhaust Gas Emission of Cars with Spark-Ignition Engines

Marcin Rabe [1,*], Agnieszka Jakubowska [2], Veselin Draskovic [3], Katarzyna Widera [4], Tomasz Pudło [5], Agnieszka Łopatka [6] and Łukasz Kuźmiński [7]

1 Management Institute, University of Szczecin, 70-453 Szczecin, Poland
2 Faculty of Economic Science, Koszalin University of Technology, 75-453 Koszalin, Poland
3 Institute of Management, University of Social Sciences, 90-113 Lodz, Poland
4 Faculty of Economics and Management, Opole University of Technology, 45-758 Opole, Poland
5 Faculty of Mechanical Engineering and Mechatronics, West Pomeranian University of Technology, 70-310 Szczecin, Poland
6 Institute of Economics and Finance, University of Szczecin, 70-453 Szczecin, Poland
7 Department of Process Management, Faculty of Management, Wroclaw University of Economics and Business, 53-345 Wrocław, Poland
* Correspondence: marcin.rabe@usz.edu.pl

Abstract: Conventional fuels commonly used in cars with combustion engines and the effects of their combustion have a very negative impact on the state of the environment. The combustion of liquid fuels causes the introduction of many thousands of tons of CO_2 and other harmful substances into the atmosphere every year. That is why the authorities of many countries are introducing more and more stringent emission standards for cars with internal combustion engines, and car manufacturers are trying to meet these standards. Therefore, the aim of the undertaken research was to compile and analyze the power of spark engines in individual capacity ranges, compression ratios, efficiency, CO_2 emissions, dependence of combustion on engine capacity, dependence of CO_2 emissions on engine capacity, and dependence of combustion on engine power. The conducted research also compared the level of average selected variables related to CO_2 emission in terms of engine displacement by country of production using statistical analysis.

Keywords: emissions CO_2; combustion engines; engine capacity; statistical analysis

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1. Introduction

Air pollution emitted by cars with different types of propulsion is now becoming an increasingly important issue. The effects of air pollution are most felt in city centers, where municipal pollution adds up to transport pollution. The authorities of many countries are introducing more and more stringent emission standards for cars with combustion engines, and car manufacturers are trying to meet these standards. Due to the multiple exceedances of the amount of dust and other pollutants in the air, many Polish cities are planning to tighten emission standards or even implement complete bans on entering city centers with vehicles with combustion engines. None of the traffic bans in city centers on emissions apply to cars and other vehicles equipped with electric propulsion, as these vehicles do not emit air pollutants at the place of their use. At this point, hydrogen should also be mentioned as a fuel commonly used in today's cars. Of course, this type of fuel does not produce CO_2. According to the national inventory report of 2016 [1], made by KOBIZE (National Center for Emissions Management and Balancing), the main source of CO_2 emissions in Poland is the combustion of fuels. The share of this category accounted for 91.8% of total CO_2 emissions in 2021. The shares of the main subcategories are as follows:

- from the energy industry = 51.51%
- from manufacturing and construction = 9.58%

- with transport = 14.06%
- from other sectors = 16.65%

Carbon dioxide emissions are treated as a determinant of pollutant emissions. Carbon dioxide is perceived by many institutions as a poison, and this is not really the case. Carbon dioxide is formed during the combustion of coal and all kinds of hydrocarbons, and its amount in fact speaks of the amount of fuel burned [2,3]. Much more important are the other components of combustion that escape from the exhaust pipes of vehicles with internal combustion engines and the chimneys of power plants and combined heat and power plants, which directly affect the health and life of people [4–6].

Analyzing the development of the situation on the automotive market, one can notice a tendency to change in the direction of pro-ecological changes. For several decades, there has been a development of legal conditions tightening the requirements for motor vehicles, and in particular their engines, which have recently become more and more ecological and economical at the same time. Initially, this development was associated with the improvement of energy properties of engines mainly affecting the improvement of vehicle dynamics. In the years of the global fuel crisis, economic trends have come to the fore, and in recent times environmental conditions have played a decisive role [7–9]. All these factors have in common the feature of making the best use of the energy stored in the available fuel.

The combustion process associated with the production of energy for automotive purposes is one of the main sources of environmental pollution, among which CO_2 CO, SO_2, CH, PM as well as NO_X and many other compounds dominate. Means of transport are among the most serious pollutants [10,11]. In Europe, around 12% of CO_2 emissions come from motor vehicles. The high economic level, especially of highly industrialized countries, forces a spontaneous increase in the number of means of transport that cause environmental pollution. It can be noted that to burn 1 kg of gasoline, you need a similar amount of air that an adult person consumes on average during the day and, in the case of a passenger car, it is a matter of driving several kilometers [12–14].

Urban agglomerations are particularly exposed to high air pollution by exhaust fumes of cars filling city streets. The risk of emissions depends mainly on the number of vehicles, but also on the technical condition of the engines and their accessories and the technologies used in them, which can be seen in the example of similar tests [15]. It is assumed that the emission of harmful exhaust components is to a large extent related to the age and operating mileage of vehicles. The issues of interest undertaken in this field, however, do not correspond to the advancement of the available scientific achievements. Despite the knowledge about cars with spark-ignition engines accumulated in a multi-source manner, there is a noticeable lack of many theoretical and empirical explanations regarding the data presented by car manufacturers in sales catalogs. The study used a detailed specification of comparable engines reported by brand manufacturers. [16]. Therefore, the aim of the undertaken research was to compile and analyze the power of spark engines in individual ranges of capacity, compression ratios, efficiency, CO_2 emissions, dependence of combustion on engine capacity, dependence of CO_2 emissions on engine capacity, and dependence of combustion on engine power.

2. Literature Review

Conventional fuels commonly used in cars with combustion engines and the effects of their combustion have a very negative impact on the state of the environment. The combustion of liquid fuels causes the introduction of many thousands of tons of CO_2 and other harmful substances into the atmosphere every year. In addition, there is a high risk of soil and water pollution associated with the extraction, storage and storage of liquid fuels. The European Union is trying to introduce specific requirements to reduce environmental pollution by internal combustion vehicles [17,18].

Today, there are many definitions of the term pollution. In accordance with Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, the term 'gaseous pollutants' means carbon monoxide emissions, nitrogen oxides, expressed as equivalent to nitrogen dioxide (NO_2) and hydrocarbons [19–21]. That Regulation also defines the concept of exhaust emissions from the exhaust system as emissions of gaseous and particulate pollutants. The definition of pollution is also contained in Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe [22,23]. According to these regulations, a pollutant is any substance in the air that is likely to have harmful effects on human health and/or the environment as a whole. In accordance with the provisions of the Act of 27 April 2001, environmental law dictates that we understand pollution as emissions that are harmful to human health or the state of the environment, cause damage to material goods, worsen the aesthetic qualities of the environment or interfere with other, legitimate ways of using the environment. Exhaust gases as a mixture of gases escaping from the internal combustion engine, which is a product of fuel combustion, have a negative impact on the environment. In the combustion process, hydrocarbons (fuel) and air are converted into a mixture of gases called exhaust gases. The exhaust gases include such substances as carbon dioxide CO_2, carbon monoxide CO, nitrogen oxides NO_X, HC hydrocarbons, water vapor H_2O, Nitrogen N, Oxygen O_2, sulfur oxides SO_X, and particulate matter. It is impossible to indicate here the exact composition of the exhaust gases, which depends on both the type of engine and the type and composition of the fuel. Some of the gases that make up the exhaust gases are inert to human beings and the environment, but most of them have adverse effects on both [24,25].

Currently, Regulation (EU) 2018/8421 of the European Parliament and of the Council requires Member States to meet the Union's target of reducing greenhouse gas emissions by 40% below 2005 levels by 2030. This applies to sectors that are not covered by the EU Emissions Trading System. A significant proportion of emissions from these sectors comes from road transport. Moreover, it is on an upward trend and remains well above 1990 levels. A further increase in emissions in this area may consequently offset the reductions achieved by other sectors in the fight against climate change. For this reason, the European Commission is taking further steps to reduce pollution caused by cars, making this issue a priority [26].

Since the beginning of the nineties of the last century, the Union has been constantly tightening the emission standards set for car models and other vehicles in order to combat the growing air pollution. Each set of standards, from the first (EURO 1/1991) to the last, imposed limits on the total amount of exhaust emissions, in particular: carbon dioxide (Table 1). The key objective of these standards is to improve air quality by reducing the most important harmful components of exhaust gases.

The manufacturers' response to these requirements was the use of various new technologies in internal combustion engines. For some time, however, the requirements set by subsequent standards have been difficult to achieve. Therefore, car companies began to use drive systems combining an internal combustion engine and an electric one, called hybrids, and in extreme cases drive systems that are purely electric. Although they help to achieve the imposed limit of Euro standards, on the other hand, they significantly increase the price of the vehicle [27].

According to the Euro 6 standard, which has been in force for new cars since September 2015, they must not emit more than 120 g of CO_2 (on average) [28] per kilometer driven at the place of use. This level of CO_2 emissions translates into an average fuel consumption of no more than 5.6 l per 100 km. Reducing the amount of fuel consumption and reducing the emission of harmful pollutants is associated with a significant complexity in the design of internal combustion car engines. Manufacturers of cars with combustion engines have mastered the art of reducing CO_2 and pollutant emissions only during laboratory tests according to NEDC (New European Driving Cycle). The actual road fuel consumption is therefore about 38% higher than declared by the manufacturers of cars with internal combustion engines. The discrepancy between actual emissions and those declared by car manufacturers is getting bigger every year [29]. Even greater differences are to be expected between the declared and actual emissions of other toxic compounds contained in the exhaust gases. A published study commissioned by the Baden-Württemberg State Office for the Environment, Measurement and Nature Conservation shows that modern diesels that meet the latest Euro 6 standard emit an average of 8.5 times more nitrogen oxides (NOx) than the standard allows on road [30]. Nitrogen oxides, unlike CO_2, pose a real threat to human life and health. However, limiting the amount of nitrogen oxides in the exhaust gas requires a reduction in temperature and pressure during fuel combustion, which unfortunately reduces the efficiency of the internal combustion engine. Keeping the engine power unchanged would require an increase in the amount of fuel burned, which in turn is disadvantageous for drivers and car manufacturers and entails difficulties in meeting the CO_2 emission standard. In modern internal combustion engines, the aim is only to reduce displacement and CO_2 emissions. The constant increase in engine power causes the fuel to burn at very high temperatures and pressures, which in turn promotes the improvement of efficiency, but it greatly increases the emission of nitrogen oxides, while at the same time also promoting lower emissions of particulate matter considered to be very dangerous to human health and life [31]. Meanwhile, the ecological dimension of human well-being is increasingly appreciated now [32–34], which, in turn, facilitates the development of responsible practices in manufacturing [35,36], especially in the face of energy poverty risks [37].

Table 1. List of Euro1–7 standards.

Standard	**Entry into Force**	**Carbon Monoxide Emissions [g/km]**	**Emissions of Hydrocarbons [g/km]**	**Emission of Volatile Organic Compounds [g/km]**	**Emissions of Nitrogen Oxides [g/km]**	**NOx Emissions + Hydrocarbons [g/km]**	**Particulate Emissions [g/km]**	**Solid Particle Number [1/km]**
Euro 1	July 1992	2.72				0.97		
Euro 2	January 1996	2.2				0.5		
Euro 3	January 2000	2.3	0.20		0.15	(0.35)		
Euro 4	January 2005	1.0	0.10		0.08	(0.35)		
Euro 5a	September 2009	1.0	0.10	0.068	0.060	(0.18)	0.005	
Euro 5b	September 2011	1.0	0.10	0.068	0.060	(0.16)	0.0045	
Euro 6b	September 2014	1.0	0.10	0.068	0.060	(0.16)	0.0045	6×10^{11}
Euro 6c		1.0	0.10	0.068	0.060	(0.16)	0.0045	6×10^{11}
Euro 6d −Temp	September 2017	1.0	0.10	0.068	0.060	(0.16)	0.0045	6×10^{11}
Euro 6d	January 2020	1.0	0.10	0.068	0.060	(0.16)	0.0045	6×10^{11}
Euro 7	(2025)	(1.0)			(0.030)	(0.13)		

Source: Own elaboration on the basis of dieselnet.com, accessed on 20 July 2022.

Many European Union countries, in order to increase demand for these more expensive cars, introduce incentives in the form of discounts, which aim to encourage potential buyers to buy hybrid or electric vehicles. Currently, work is underway on the introduction of a new EURO 7 standard, which is part of the EU climate policy reform project announced in 2019 (the so-called European Green Deal). It includes a set of European Commission policy initiatives with the overarching aim of achieving climate neutrality in Europe by 2050.

The work on the EURO 7 standard is also referred to in the package announced in July 2021, in which the Commission proposed a 100% reduction in emissions for new sales of cars and vans from 2030. The project assumes, i.e., the introduction of the obligation to measure exhaust emissions in real operating conditions (not in the laboratory), the so-called Permanent Magnet Synchronous Motor (PEMS) system. Changes in emission allocations are to be assessed as part of the upcoming Euro 7 impact assessment. The assumptions of the new EURO 7 standard are being worked on by the so-called Advisory Group on Vehicle Emission Standards (AGVES), operating at the European Commission. In its initial recommendations for EURO 7, AGVES proposed far-reaching emission reductions: CO_2 levels would fall to 30 g/km (from the current 95 g/km) and nitrogen oxide emissions would be set at 30 mg/km. The implementation of such solutions would make it so that even hybrid cars would have a serious problem with meeting the new standard, and as a result, they could not be sold in the EU. Such a strict standard would mean a de facto ban on the sale of cars with internal combustion engines from 2035.

Already at the moment, some Member States of the European Union have announced or are already implementing a policy of 100% sales of zero-emission vehicles. These are Iceland, Denmark, Sweden (from 2030), Norway, Slovenia, Germany, France, The Netherlands, Spain (from 2040) and Portugal.

On the other hand, the European Commission assumes that in 2050 only zero-emission vehicles will be used on the territory of the European Union. However, it is already planned to introduce another standard, Euro 7. The date of its entry into force is not yet known, but work is already underway, and it is expected that its implementation may take place by the end of 2025 [38].

3. Research Method

A car is a self-propelled motor vehicle (engine) and energy carriers, designed to move on the roads [39–41]. The word 'car' was created as a result of winning a competition for a typically Polish word for automobile written before World War II. The adopted name comes from the words 'alone' and 'walk', that is, it defines a self-propelled vehicle.

For the formal introduction of the term 'internal combustion engine', an energy converter should be specified. It is a device that converts energy from one type to another type, e.g., kinetic energy of air (wind) into mechanical energy, or the energy of chemical bonds into electrical (electrochemical cell). Motors are energy converters that convert any type of energy into mechanical energy, and heat motors are motors that convert heat into mechanical energy. Heat engines are divided into external combustion engines and internal combustion engines, that is, internal combustion engines. Among internal combustion engines, piston internal combustion engines have found common use in car drives, mainly with sliding pistons. Due to the combustion system, i.e., the initiation of combustion, internal combustion engines are divided into engines [42,43]: spark-ignition or compression-ignition.

The original concept in the description of environmental pollution by internal combustion engines and motor vehicles is emissions. This is the mass of pollutants introduced into the environment. The limit of the carbon monoxide emission target shall be calculated as the average emission in the manufacturer's range. It is an important factor influencing the directions of development of automotive companies and the technical solutions used. This relationship results from the imposition of penalties in the event of failure to achieve the goal. Figure 1 shows the target average CO_2 emissions in the European Union.

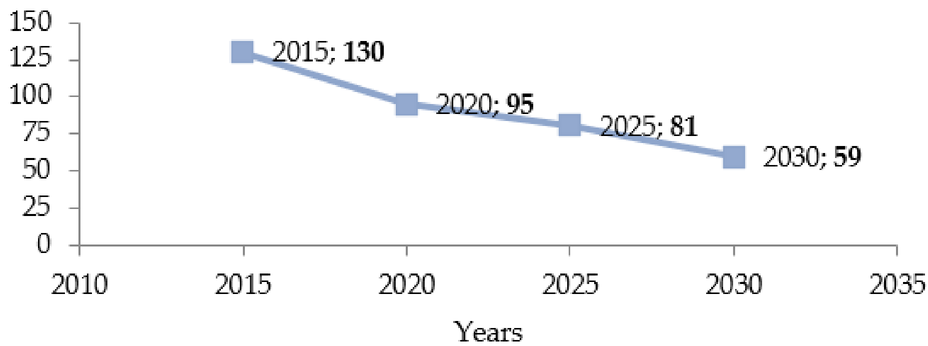


Figure 1. Graph of the target average CO_2 emissions [g/km]. Source: Own elaboration on the basis of dieselnet.com [44].

Currently, the penalty for exceeding this limit is calculated according to the Formula (1):

$$the\ amount\ of\ the\ penalty = 95\,€ \times n \times (e - e_0) \quad (1)$$

where: n = number of vehicle registrations in a given year, e = average emissions of the range of a given manufacturer in a given year, e_0 = target CO_2 emissions [45].

Tests of exhaust emissions and harmful substances of motor vehicles are carried out using the so-called measurement cycles. Up to the Euro 2 standard, this test consisted of performing the following tests separately with the vehicle: the Urban Driving Cycle (UDC) (1970) (urban driving) and Extra-Urban Driving Cycle (EUDC) (1990) (extra-urban driving) cycles in the conditions of an engine warmed up to operating temperature (this lasted 40 s each time). From Euro 3 to Euro 6, the NEDC test was used. It was performed as a whole, and it consists of four UDC cycles and one EUDC. A summary of these three tests is presented in Table 2.

Table 2. Test cycles before the introduction of WLTP.

Parameters	UDC	EUDC	NEDC
Distance (km)	0.99	6.96	10.93
Total time (s)	195.00	400.00	1180.00
Idle speed(s)	57.00	39.00	267.00
Average speed (km/h)	18.35	62.59	33.35
Average travel speed (km/h)	25.93	69.36	43.10
Maximum speed (km/h)	50.00	120.00	120.00

Source: Developed on the basis of dieselnet.com, accessed on 20 July 2022.

Since 2017, a Real Driving Emissions (RDE) test has been added to laboratory tests to check whether the results obtained are reflected in the actual driving. This is due to a decrease in performance during laboratory testing, and thus emissions. In 2017, the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) test was also used, which is designed to differentiate the different phases of the test more. It is performed for each variant of the car separately. For the purposes of the test, cars are divided into classes, while the test is divided into speed categories: Low, Average, High or Very High (Table 3).

Table 3. Division of vehicles into classes.

Category	Power/Weight Ratio (W/kg)	Maximum Speed (km/h)	Speed Tests
Class 3b	more than 34	from 120	Low 3 + Average 3–2 + High 3–2 + Very high 3
Class 3a		less than 120	Low 3 + Average 3–1 + High 3–1 + Very high 3
Class 2	above 22 to 34	-	Low 2 + Average 2 + High 2 + Very high 2
Class 1	up to 22	-	Low 1 + Average 1

Source: Developed on the basis of dieselnet.com, accessed on 20 July 2022.

In addition to eliminating emissions of substances harmful to the environment, an additional goal of manufacturers, in addition to eliminating emissions of harmful substances, is also to achieve the highest thermal efficiency, calculated according to the Formula (2):

$$\eta_c = \frac{L_i}{Q_d} \quad (2)$$

where: η_c = thermal efficiency, L_i = actual work obtained in the engine circuit, Q_d = heat supplied to the engine [45].

4. Methodological Assumptions

Spark-ignition engines perform their work by burning the fuel–air mixture as a result of a high-energy spark passing between the electrodes of the spark plug. Over time, the engines became more and more efficient. Since the beginning of the 1990s of the twentieth century, more and more emphasis has been placed on the gradual reduction of emissions of substances harmful to the environment. Looking for ways to solve this issue, engineers in some automotive companies involved in the design of engines decided to use those with a smaller capacity and/or fewer cylinders and supplemented them with engine supercharging since such an engine design had lower power: namely one or more turbines, or compressors, or in extreme cases, a combined system of the compressor and turbine.

Such engines began to appear at the beginning of the twenty-first century. However, not all manufacturers have agreed to this technology [46,47]. A spark-ignition engine is an internal combustion heat engine in which a combustible mixture is fed into the cylinder. Preparation of the combustible mixture must be sufficient in advance before the combustion period and usually outside the cylinder (except for direct injection engines). The combustible mixture is compressed and then ignited by a foreign ignition source—an electric spark. At the time of ignition in the combustion chamber, there is the entire amount of combustible mixture intended for combustion in a given circuit [48,49]. The theoretical circuit that maps the phenomena occurring in the engine cylinder is the Otto circuit. It is a circuit with heat supply at a constant volume. Combustion takes place in a short time, with a little changing volume of the combustion chamber, i.e., the volume above the piston.

The aim of the conducted research was to perform the following summaries and analysis:

- Engine power in individual capacity compartments;
- Compression ratio;
- Medium combustion (in figures it is expressed in l/100 km);
- Power dependence on engine capacity;
- CO_2 emissions;
- Combustion dependence on engine capacity;
- CO_2 emissions dependence on engine capacity;
- Combustion dependence on engine power;
- Dependence of CO_2 emissions on engine power.

The study used technical data of individual brand manufacturers, which were taken from the original sales catalogs offered by the manufacturers in Europe, Asia and the USA. These data are a factual section with detailed information about cars, with specific data and figures.

The study took into account the current state of the art of spark-ignition power units used in passenger car brands of European and Asian manufacturers, based on the current offer of passenger car manufacturers (as of 1 January 2021). The criteria for the selection of engines were as follows:

1. The largest possible and latest technical engine in the range (for >2001 the engine closest to the capacity of 3000 cm^3 was chosen);
2. If the engine had multiple power variants, the most powerful one was chosen;
3. If a version with a given power was offered in many models, the performance and emissions refer to the smallest car with this engine variant.

For research purposes, a compilation of technical data of engines of individual brands in capacity ranges was also adopted: less than 1000 cm^3, 1001–1500 cm^3, 1501–2000 cm^3 or above 2001 cm^3.

The study also made a similar comparison of individual American car brands taking into account the following units in force in the United States: distance [mile] = 1.609 km; volume [gallon] = 3.785 L. Instead of burning in liters per 100 km, there is the concept of fuel economy, which measures the number of miles traveled on one gallon (MpG). They shall be calculated as Equation (3), as follows [45]:

$$(\mathrm{MpG}) = \frac{100 \times 3785}{1609 \times [\mathrm{L}/100\ \mathrm{km}]} \tag{3}$$

The study also used a compilation of technical data of engines of individual American brands in capacity ranges: less than 2000 cm^3, 2001–3700 cm^3 or above 3701 cm^3.

According to the catalog data of the cars with a positive-ignition engine selected for testing, the lowest fuel consumption is 4.2 L/100 km for driving in the road cycle, and 4.6 L/100 km in the urban cycle. The highest fuel consumption is 24 L/100 km for the urban cycle and 13 L/100 km for the road cycle.

5. Test Result

The following Figures 2–19 show the following analyses of engine power in individual displacement compartments, compression ratio, medium combustion, power dependence on engine capacity, CO_2 emissions, combustion dependence on engine capacity, dependence of CO_2 emissions on engine capacity, dependence of combustion on engine power, dependence of CO_2 emissions on engine power, and dependence of CO_2 emissions on engine power.

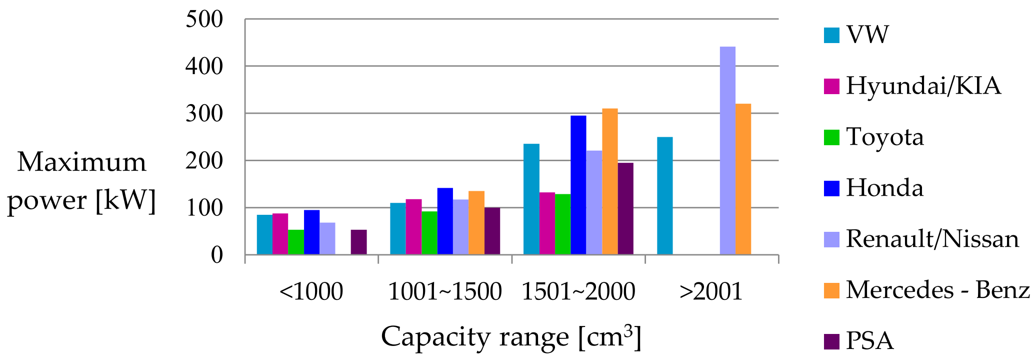


Figure 2. Maximum power in each engine capacity compartment; European and Asian car brands. Source: Developed own.

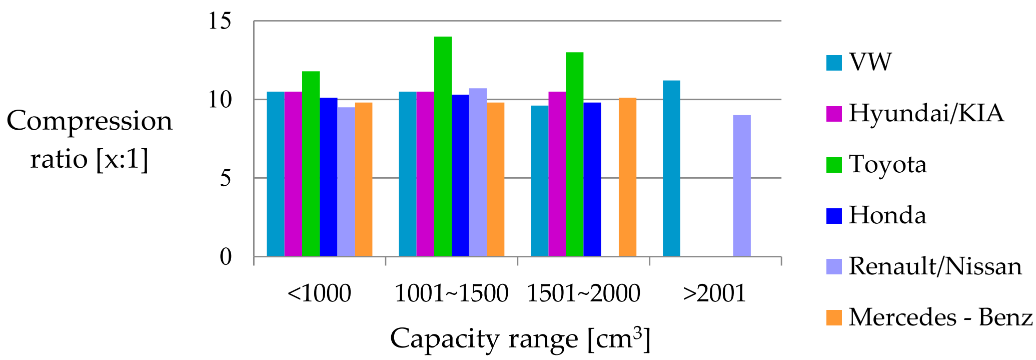


Figure 3. Compression ratio in the individual engine capacity compartments; European and Asian car brands. Source: Developed own.

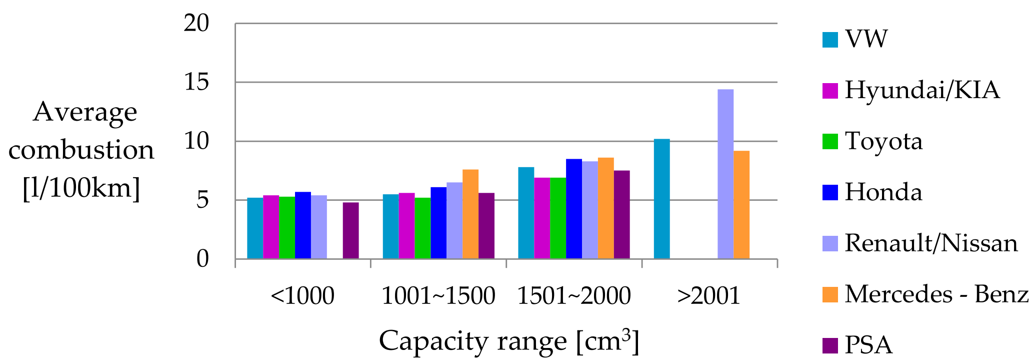


Figure 4. Average fuel consumption per engine capacity compartment; European and Asian car brands. Source: Developed own.

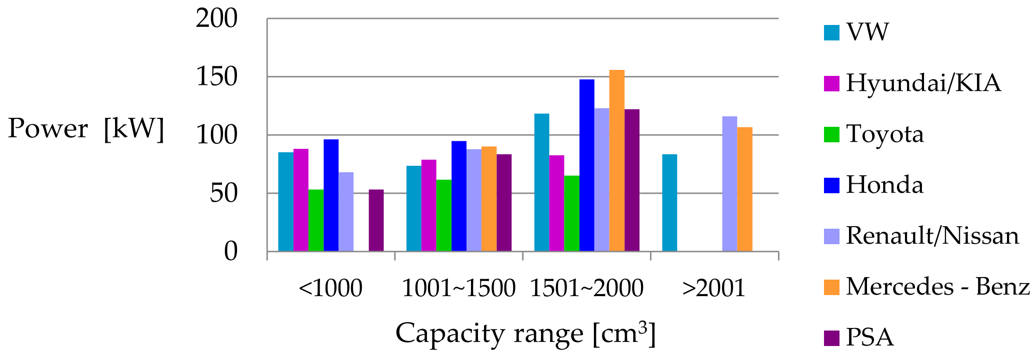


Figure 5. Engine power per liter of displacement in the different engine displacement compartments; European and Asian car brands. Source: Developed own.

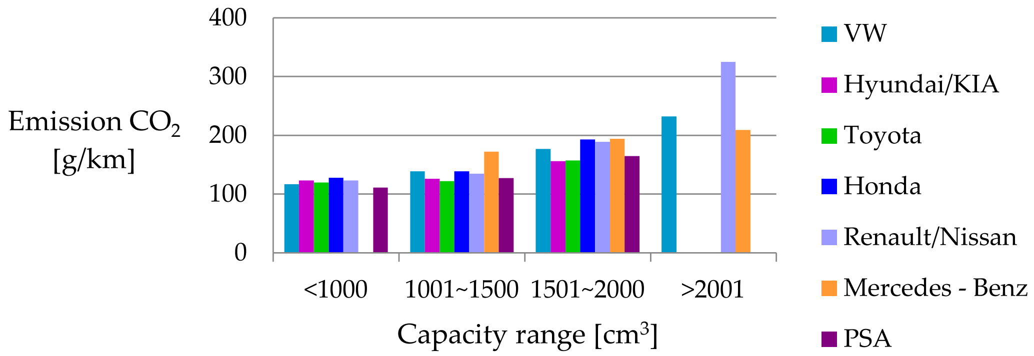


Figure 6. CO_2 emissions in individual engine displacement compartments; European and Asian car brands. Source: Developed own.

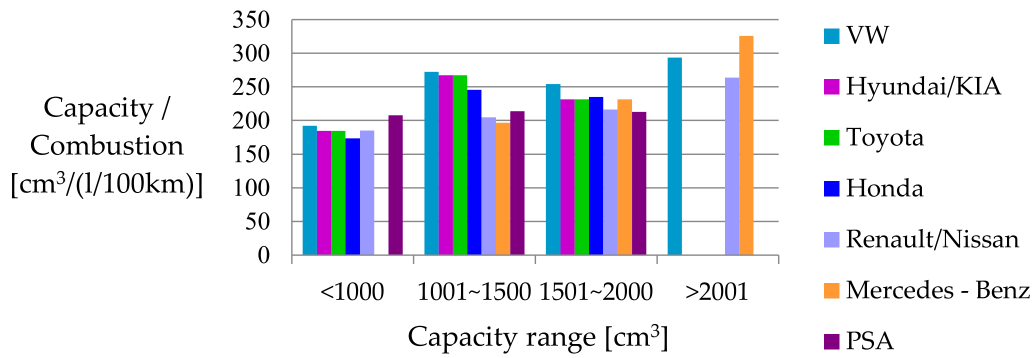


Figure 7. The ratio of displacement to combustion in the individual engine capacity compartments; European and Asian car brands. Source: Developed own.

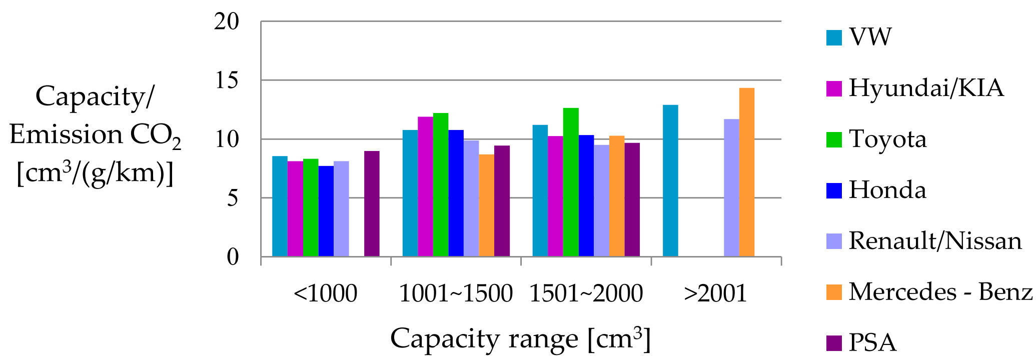


Figure 8. The ratio of engine capacity to emissions in each capacity compartment; European and Asian car brands. Source: Developed own.

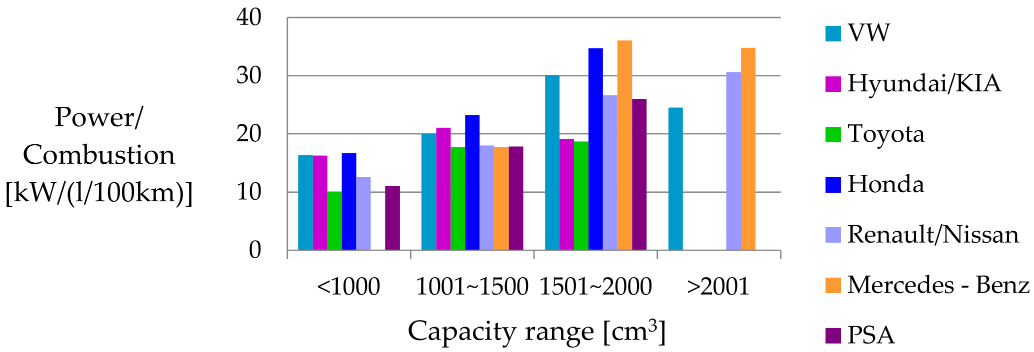


Figure 9. The ratio of maximum power to combustion in the individual engine capacity compartments; European and Asian car brands. Source: Developed own.

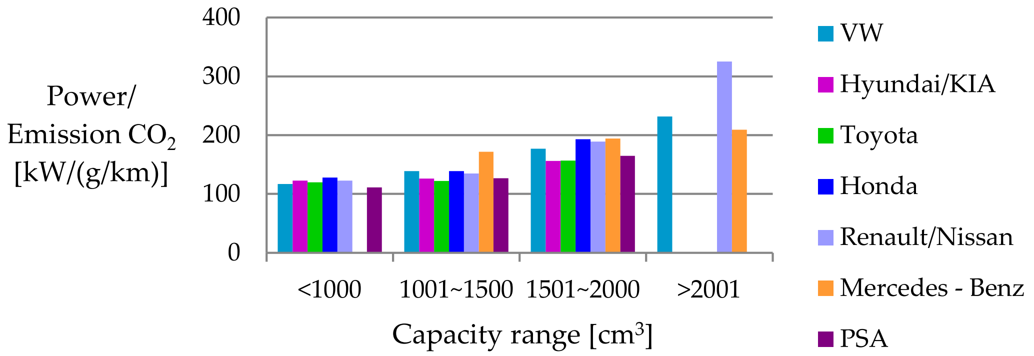


Figure 10. The ratio of maximum power to carbon dioxide emissions in the different engine capacity compartments; European and Asian car brands. Source: Developed own.

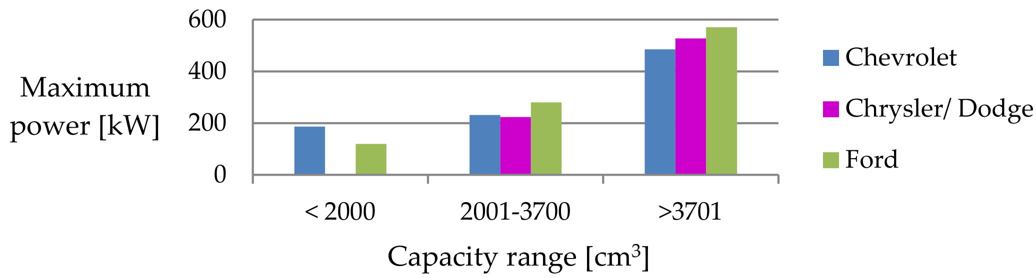


Figure 11. Maximum power in individual engine capacity ranges among American car brands. Source: Developed own.

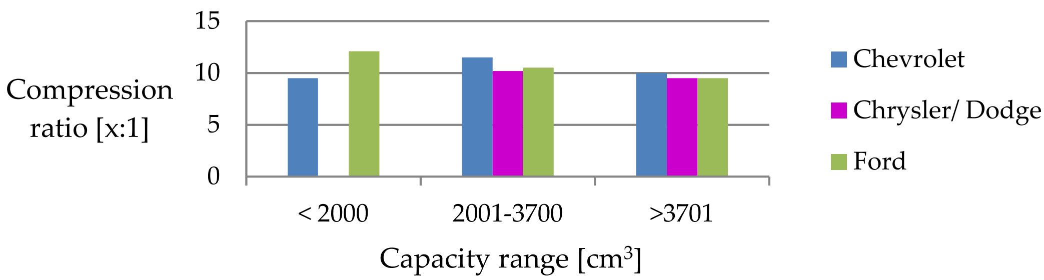


Figure 12. Compression ratios in individual capacity ranges among American car brands. Source: Developed own.

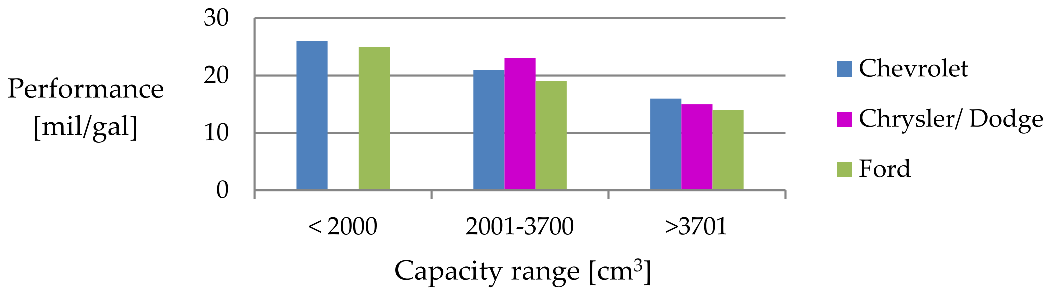


Figure 13. Performance in individual engine capacity ranges among American car brands. Source: Developed own.

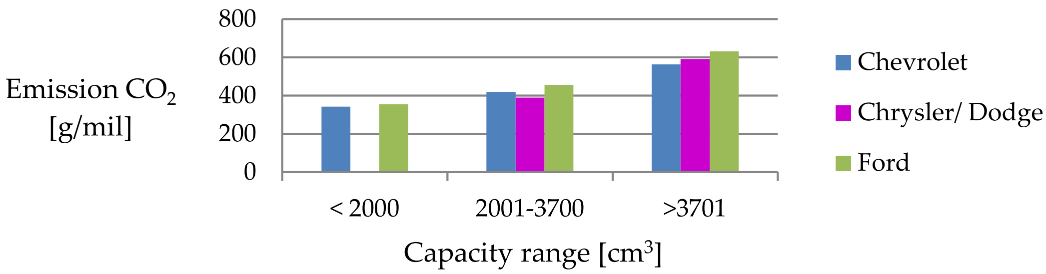


Figure 14. Carbon dioxide emissions in individual engine capacity ranges among American car brands. Source: Developed own.

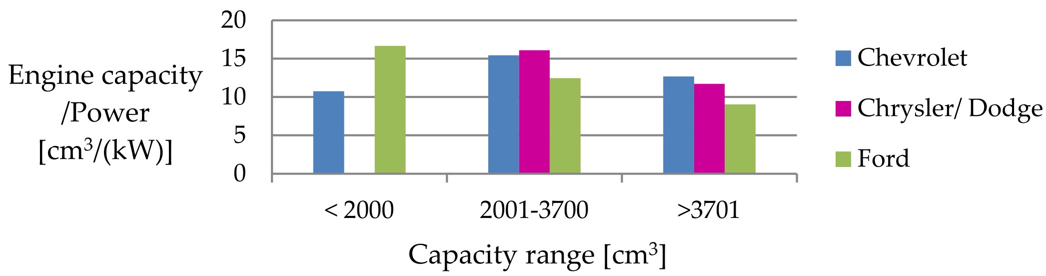


Figure 15. Ratio of engine capacity to power in individual engine capacity compartments among American car brands. Source: Developed own.

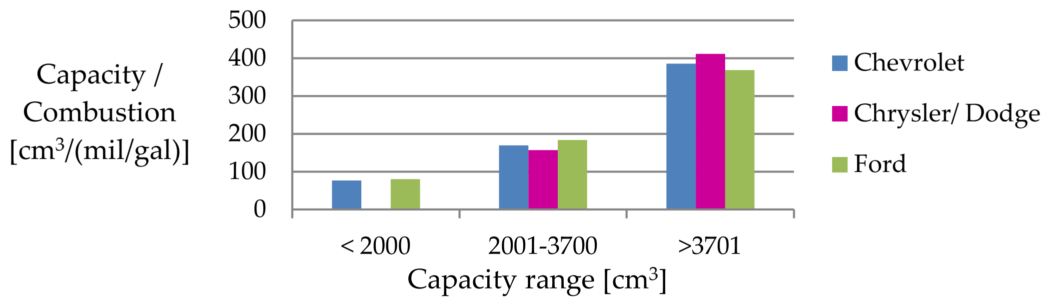


Figure 16. Ratio of capacity to combustion in individual engine capacity ranges among American car brands. Source: Developed own.

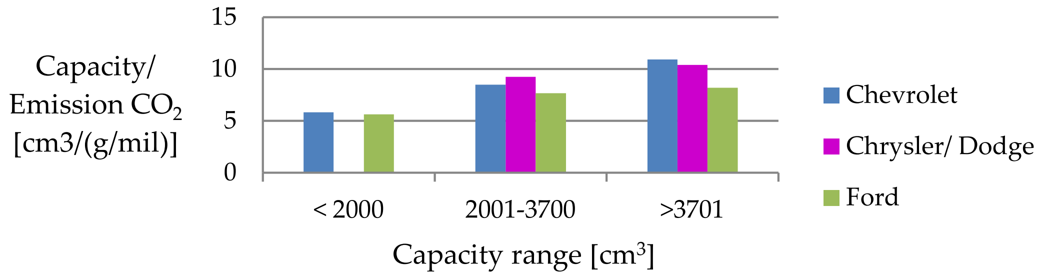


Figure 17. Ratio of capacity to carbon dioxide emissions in individual engine capacity ranges among American car brands. Source: Developed own.

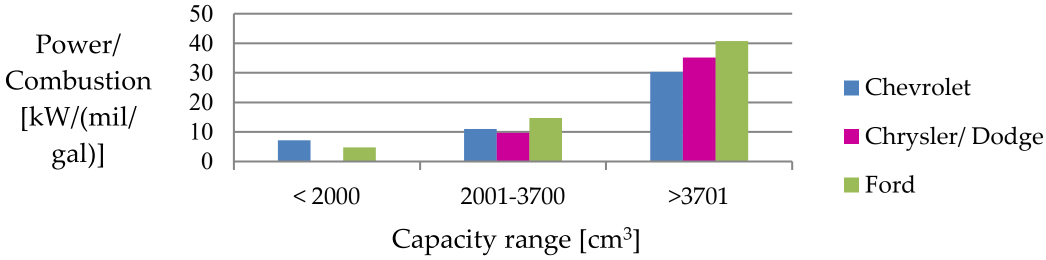


Figure 18. Ratio of engine power to combustion in individual engine capacity ranges among American car brands. Source: Developed own.

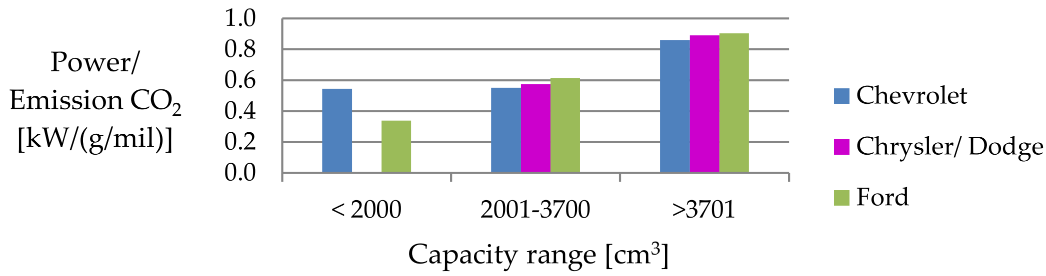


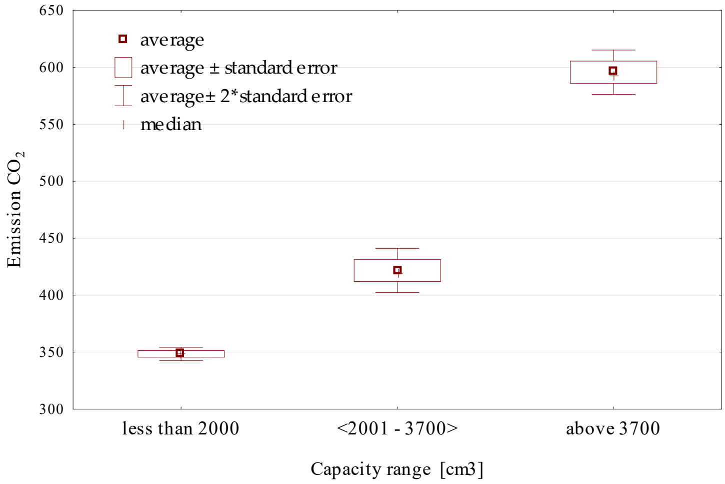
Figure 19. Ratio of engine power to carbon dioxide emissions in individual engine capacity ranges among American car brands. Source: Developed own.

Based on Figures 2 and 3 above, it can be concluded that the Honda and Mercedes-Benz concern engines have the most power, and that the Toyota engine has the least but at the same time is characterized by the highest compression ratio.

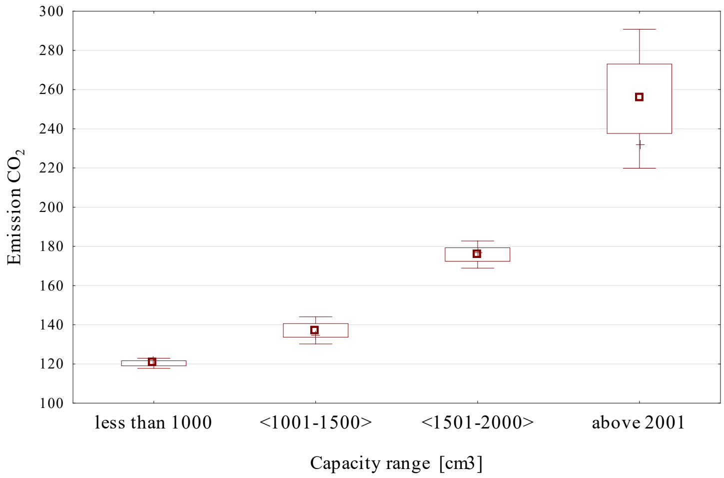
A comparative analysis of car groups was also carried out in terms of the following variables: Emission CO_2, Capacity/Emission CO_2, Power/Emission CO_2. The variable categorizing into independent groups was the category according to the engine displacement. The analysis concerned cars produced in America, Europe, and Asia separately.

The existence of statistically significant differences in the levels (average) of the above-mentioned variables between the examined categories of cars was examined. The level of significance in the study was $\alpha = 0.05$. The division into categories is in line with the information provided in the Description of the research section. Due to the fact that the values from which the researched variables were determined are technical parameters provided by car manufacturers, it was assumed that the analysis concerns representatives of the indicated brands and models. Table 4 lists the values of the Kruskal–Wallis statistics used to assess whether there is a statistically significant difference between the studied groups in the level of the studied variables.

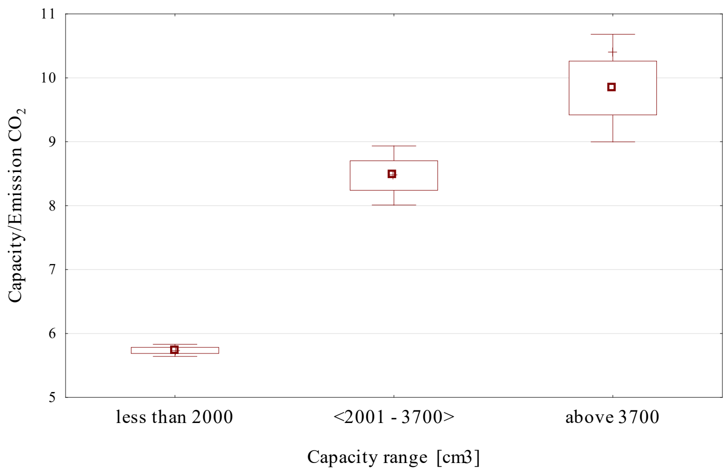
At the level of significance $\alpha = 0.05$, we find that there are significant statistical differences in the levels of averages of the tested variables between the categories of tested cars, because for all values of statistics the p-value is lower than the level of significance adopted in the study. Figure 20a–f show the distributions of the variables studied by engine displacement categories.



(**a**)

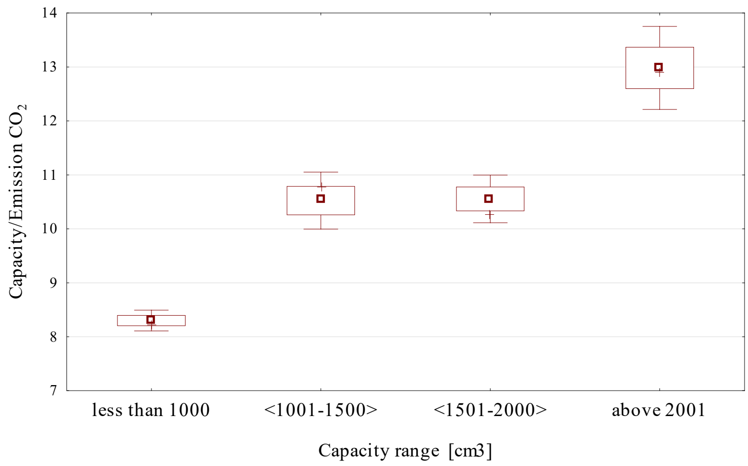


(**b**)

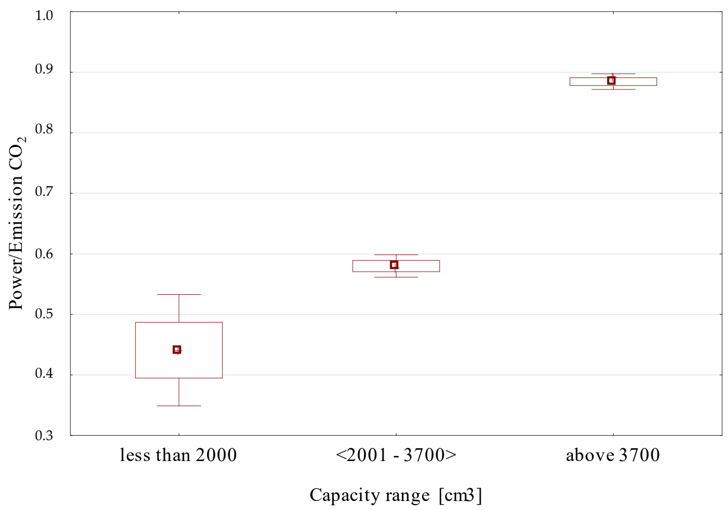


(**c**)

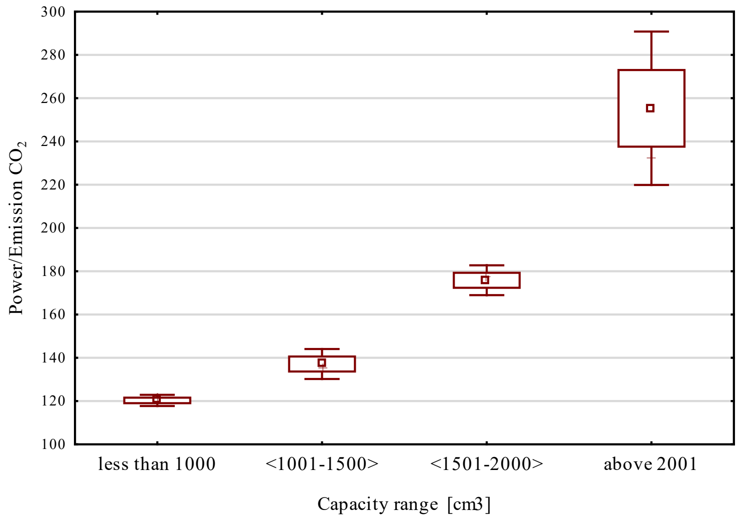
Figure 20. *Cont.*



(**d**)



(**e**)



(**f**)

Figure 20. (**a**–**f**). Distribution of the values of the studied variables divided into categories of capacity range [cm^3]. Source: Developed own.

Table 4. Verification of the statistical significance of differences in the levels of variables between car categories.

Variables	Personal Cars			
	European and Asian		American	
	Test Kruskal-Wallisa			
	Value of the Statistic	*p*-Value	Value of the Statistic	*p*-Value
Emission CO_2	56.197	0.0000	20.536	0.0000
Capacity/Emission CO_2	46.892	0.0000	15.424	0.0004
Power/Emission CO_2	56.197	0.0000	20.536	0.0000

Source: Developed own.

6. Discussion

The analysis of the distributions of the studied variables indicates the need for more detailed verification of the differences in their level. Thus, the Mann–Whitney U test examined which pairs of the capacity range variable category [cm^3] differentiate the studied variables in a significant way. The results obtained for cars produced in Europe and Asia and America are included in Tables 5 and 6.

Table 5. *p*-values for differences in the levels of the variables tested by engine displacement categories of American-made cars.

Category	Less than 2000	<2001–3700>	Above 3701	Variables
less than 2000		0.1325	0.0000	Emission CO_2
<2001–3700>	0.1325		0.0208	
above 3701	0.0000	0.0208		
less than 2000		0.0324	0.0003	Capacity/Emission CO_2
<2001–3700>	0.0324		0.4008	
above 3701	0.0003	0.4008		
less than 2000		0.1325	0.0000	Power/Emission CO_2
<2001–3700>	0.1325		0.0208	
above 3701	0.0000	0.0208		

Source: Developed own.

Table 6. *p*-values for differences in the levels of the variables tested broken down by engine displacement categories of cars manufactured in Europe and Asia.

Category	Less than 1000	<1001–1500>	<1501–2000>	Above 2001	Variables
less than 1000		0.0735	0.0000	0.0000	Emission CO_2
<1001–1500>	0.0735		0.0054	0.0000	
<1501–2000>	0.0000	0.0054		0.2496	
above 2001	0.0000	0.0000	0.2496		
less than 1000		0.0000	0.0000	0.0000	Capacity/Emission CO_2
<1001–1500>	0.0000		1.0000	0.0318	
<1501–2000>	0.0000	1.0000		0.0375	
above 2001	0.0000	0.0318	0.0375		
less than 1000		0.0735	0.0000	0.0000	Power/Emission CO_2
<1001–1500>	0.0735		0.0054	0.0000	
<1501–2000>	0.0000	0.0054		0.2496	
above 2001	0.0000	0.0000	0.2496		

7. Conclusions

1. Based on the Figures 2–19 above, it can be concluded that:
    - Toyota engines are as economical as engines from other manufacturers, but they have little power;
    - Mercedes-Benz engines have the highest fuel consumption, but they are adequately strong;

- in the range below 1000 cm^3, CO_2 emissions and combustion, and therefore also the ratio of engine capacity-combustion-CO_2 emissions, is at a very even level, while the difference in power is due to the use of a turbocharger;
- in the range from 1001 cm^3 to 1500 cm^3, VW, Hyundai/KIA and Honda have a high power-to-combustion ratio;
- in the range from 1501 cm^3 to 2000 cm^3, Mercedes-Benz and Honda have the highest power-to-combustion ratio;
- in the range above 2001 cm^3, few manufacturers have engines with this capacity, but they have better power-to-emission ratios;
- based on the above data, it can be concluded that the Ford brand has the most optimized engines.

2. When analyzing Figure 20a,c,e and Table 5, it can be noticed that there are no statistically significant differences in the levels of the variable (p-value > 0.05):
    - Emission CO2 and Power/Emission CO2 between cars with the smallest (less than 2000) and average (<2001–3700>) engine displacement;
    - Capacity/Emission CO2 between cars with medium (<2001–3700>) and highest (above 3701) engine displacement.
3. On the other hand, the analysis of Figure 20b,d,f and Table 6 proves that there are no statistically significant differences in the levels of the variable:
    - Emission CO2 and Power/Emission CO2 between cars with the smallest (less than 2100) and category <2001–3700> engine displacement and between the highest (above 2001) and category <1501–2000> engine displacement;
    - Capacity/Emission CO2 between cars of category (<1001–1500>) and <1501–2000> of engine displacement.

8. Summary

The negative impact of the automotive industry on the natural environment necessitates the search for possible ways to protect it against excessive contamination, which will consist, i.e., in tightening the applicable exhaust gas toxicity standards and introducing a reduction in fuel consumption by newly registered cars and refining traditional fuels, or the use of alternative fuels. The reaction of vehicle manufacturers will probably be, on the one hand, the development of more economical cars, and on the other hand, the dissemination of alternative drives (electric, hybrid, gas). The research shows that there are no statistically significant differences in the levels of the variable CO_2 emission and Power/CO_2 emission between cars with the smallest and average engine displacement. On the other hand, the analysis shows that there are no statistically significant differences in the levels of the variable CO_2 Emissions and Power/CO_2 Emissions between cars of the smallest category and between the highest engine displacement.

Research also shows that the Ford brand has the most optimized engines. In turn, the engines of the Honda and Mercedes-Benz concern have the highest power, and Toyota the smallest while at the same time having the highest compression ratio.

The implementation of the EURO 7 standard would mean that even hybrid cars would have a serious problem in meeting the new standard, and as a result, they could not be sold in the European Union. Such a strict standard would mean a de facto ban on the sale of cars with spark-ignition internal combustion engines from 2025.

It is worth adding that as part of the proposals relating to the European Green Deal, there have also been demands from the Commission that 2035 should be a border year for the production and import of cars with internal combustion engines. Such a ban would apply to all new vehicles, forcing manufacturers to completely abandon this source of propulsion. However, this is a political proposal for the time being, which for effective implementation would probably require an appropriate amendment of European Union law, including the existing treaties.

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