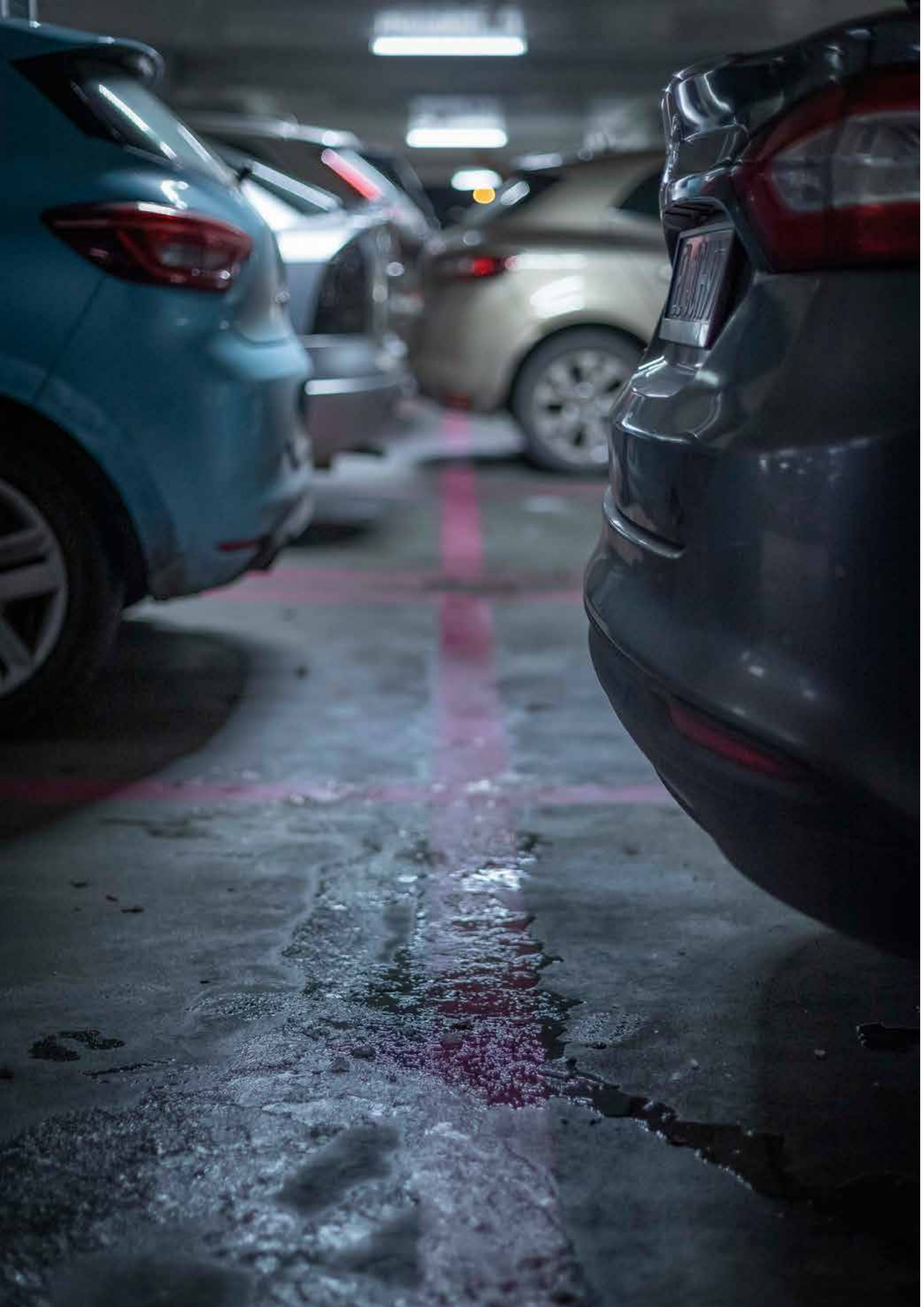

Emission performance assessment of passenger car engines: A comparative analysis

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Abstract

The automotive market is constantly developing and employing innovative technologies. The new trend of electromobility affects the whole world and is part of the transformation of the economy. Also, the European Union takes significant steps to support the development of the electric sector of the automotive market. This is confirmed by the signed declaration in Glasgow, which leads towards a ban on the sale of cars with combustion engines by 2035. Due to the initiatives taken by international institutions to green all processes in the economy and the defined legal framework, these activities have an influence on other market participants. The problem identified in this article is the actual impact of implemented solutions concerning the type of engine used in cars offered for sale in Poland. The aim of the article is accompanied by a research question, is the electric vehicle less harmful to the environment? The paper compares cars of the same producer, class and type with petrol, diesel, hybrid (petrol-electric) and electric engines in terms of the environmental impact parameters described in the methodology. The research method is a comparative analysis of SUVs of urban type. As a result of the research, it has been determined that a vehicle with an electric engine emits the least amount of carbon dioxide and is the most environmentally friendly solution.

Keywords:
BEV, ecology, environmental harm, exhaust emissions, green economy, ICE, mobility, PHEV.

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Introduction

One of the widely studied contemporary ideas or trends in economics (Graczyk et al., 2020) and management sciences is sustainable development (Sulich, 2018; Wyszomirski, 2017) and the decision-making processes associated with it (Filho et al., 2015; Łuszczyk et al., 2021). These are accompanied by growing expectations coming from the automotive industry, seeking solutions to support and simplify the process of achieving sustainability (Gontarz & Sulich, 2019). Buyers' decision-making processes include evaluating and then selecting a vehicle based on the type of powertrain used – the engine (Brach, 2019b). The choice of a particular car model may be determined not only by economic factors regarding the consumption of factors and energy carriers, but also by considerations regarding the environmental performance of the vehicle (Brach, 2019b; Gontarz & Sulich, 2019). In numerous lists, *electric vehicles* (EVs) lead the way in this aspect. Although in the early days of vehicle electrification the terms 'ecological car' were used (Babula & Pietruszczak, 2017), it was only over time that it was replaced by 'zero-emission car' (Kos et al., 2020) or "green car" (Attwood et al., 2020). Therefore, the term 'green transport', i.e. the reduction of the negative impact of transport on the environment through the use of the latest technologies, is emerging in everyday communication (Klimecka-Tatar et al., 2021). The totality of issues related to the use of electrically powered vehicles is referred to as electromobility (Sztafrowski et al., 2021), however, this concept is not only about operational issues, but also about environmental, social, economic and legal issues (Krzak, 2018). The transition from emission-based propulsion to a zero-emission, electric type of propulsion is not only a certain challenge for car manufacturers, but also an opportunity for a step towards sustainability (Sulich et al., 2020), is a search for new business models and growth strategies (Krzak, 2018). Such changes are accompanied by the development of car charging infrastructure, which ensures the success of electromobility ventures (Dankiewicz et al., 2020). In research publications, power units are rarely perfectly mapped between the vehicle types being compared (Brzeżański & Śliwiński, 2004). This is particularly true for comprehensive comparisons of petrol, diesel, hybrid and electric engines (Gontarz & Sulich, 2019; Verma et al., 2021). Therefore, the identified research gap covers not only the theoretical aspect, but also the methodological aspect in terms of the variables to be compared. Not only the engine versions, but also the vehicle production process, their operation and the sources and methods of obtaining energy factors to power the cars should be comprehensively evaluated (Matuszewska-Janica et al., 2021). In this context, the aspects of sustainability that provide the theoretical background for comparisons of car power units (engines) and their utilitarian implications to support decision-making become important (Bryman & Bell, 2007; Malewska, 2013).

The purpose of this article is to benchmark the power units of SUVs (short for *Sport Utility Vehicles*): petrol engine, diesel engine, hybrid engine and electric engine. The comparative analysis was carried out by calculating the total CO2 emissions of SUVs, assuming 270,000km travelled (Cargill & O'Connor, 2013). As a result of such a comparison, the environmental friendliness of the solution was determined by the type of propulsion used available from the manufacturer in Poland. Based on secondary data (Bieker, 2021) and own calculations, the vehicle and battery production processes, operation, conditions for obtaining fuel and/or electricity and subsequent consumption of these energy carriers were also assessed (Łuszczyk et al., 2021; Matuszewska-Janica et al., 2021). The comparisons were supplemented by calculations, the detailed content of which is included in the appendix.

The primary method adopted in the article is comparative analysis (Bryman & Bell, 2007) involving a comparison of city SUVs in different engine versions from the same manufacturer. The vehicles compared are their counterparts, which differ in the type of propulsion system. The method adopted allows similar vehicles to be compared under the same car operating conditions, subject to minor design differences affecting car performance (Bryman & Bell, 2007).

The article is organised as follows. The introduction presented justifies the reasons for taking up the topic of comparing passenger cars with different propulsion systems. The aim of the article is formulated and the research method is indicated. This was followed by a literature review. Materials and methods are discussed. A presentation of the SUVs compared was made. A summary of the emissions accompanying the production of the cars, their operation, was made. Finally, a comparative analysis taking into account the previously calculated values and a summary were included. The article includes a discussion of the results with recommendations and indicates directions for future research.

Literature review

The automotive sector is constantly looking for innovative solutions adapted to the changing needs of customers and the business environment. One of the innovations under consideration contemporarily, is electromobility (Brdulak & Pawlak, 2021). Electromobility is both about the theory and practice of electric vehicle mechanics and construction as well as management decisions (Malewska, 2013). E-mobility encompasses all issues concerning the use and operation of electric vehicles. Therefore, the term refers to both technical and operational aspects of electric vehicles, technology and charging infrastructure. New opportunities using green, renewable electricity pose challenges to countries, vehicle manufacturers, infrastructure architects and customers (Albatayneh et al., 2020; Sulich & Grudzinski, 2019). The actions of most countries in the European Union are moving towards a shift from a 'brown' economy based on fossil fuels to a green economy (Sulich & Soloducho-Pelc, 2021), of which electric vehicles are a component (Filho et al., 2015). An expression of these changes is the COP26 declaration (Oxford Analytica, 2021) signed at the 2021 United Nations Climate Change Conference in Glasgow. This document calls for a ban on the sale of internal combustion engine cars by 2035. The main thrust of such a radical measure is to realise the goals of sustainable development. In the signed declaration, the ban covers all cars that emit exhaust fumes, i.e. diesel, petrol and hybrid cars. The assumptions of this document have also been adopted by organisations active in the field of electromobility in Poland, viz: PSPA (*Polish Alternative Fuels Association*), CEE GTI (*Central and Eastern Europe Green Transport Initiative*) and EV Klub Polska – a club for electric car users in Poland. The Glasgow Declaration defines the goals of the green economy in the field of transport and operationalises the measures in practical terms (Kotak et al., 2021). The green economy goals are also supported by increasing public awareness of low-carbon transport in Europe (Klimecka-Tatar et al., 2021). Such growing public pressure, translates not only into further legislative documents, but also the implementation of technical solutions by car manufacturers (Denis & Kuczynski, 2017). One such regulation is the European EURO emissions standard (Skupniewicz, 2019). This standard is considered by many motor vehicle manufacturers to be very restrictive, considering other guidelines that have been developed (Denis & Kuczynski, 2017). EURO standards are used to minimise external costs of transport, such as environmental pollution and negative climate impacts, thanks to modern technologies (Trzensik & Swiatłoń, 2011). The adaptation of engines to the latest requirements is carried out by means of technological solutions (Merkisz et al., 2015) including DOC reactors (diesel oxidation catalyst) and DPF (diesel particulate filter). The standards described in the European standard are revised systematically every few years, which means regular work on new filters or equipping the vehicle additionally with a small electric motor booster (Malara et al., 2019; Trzensik & Swiatłoń, 2011). The introduction of further regulations also results in a downsizing of engine capacity and compliance with national and European environmental standards (Brach et al., 2021; Brzeżański & Śliwiński, 2004).

Car manufacturers are currently facing the dilemma of adapting their production strategies to an ever-evolving vehicle market (JATO, 2021; Luszczyk et al., 2021). A major challenge is to diversify the portfolio of cars offered or to specialise in a selected powertrain (Brach, 2019a, 2019b). Although internal combustion engines are well established in the market, new regulations, environmental requirements and public awareness are driving the automotive industry towards sustainability (Wyszomirski, 2017). The latest technologies represent a major challenge in terms of human resources and significantly higher costs (Trzensik & Swiatłoń, 2011). There is also uncertainty about the end result of implementing environmentally friendly solutions in motoring. Moreover, not all manufacturers of combustion vehicles have electric vehicles. Therefore, the purchaser of a vehicle is faced with an important decision regarding the choice of not only the vehicle model, but above all the type of propulsion system. According to a cursory analysis of available industry information sources (Haddadian et al, 2015; Polish Alternative Fuels Association, 2021; Żebrowski et al, 2018) it can be concluded, primarily, that the maintenance cost – TCO (abbreviation for *Total Cost of Ownership*) of an electric car compared to its combustion counterpart is lower. In contrast, its purchase itself is more expensive and represents a long-term investment (Gawron & Bernatt, 2017). In addition to economic factors, other factors such as vehicle durability, consumer tastes and the environmental impact of the car may influence the choice of a particular solution. Car owners may have a sentimental attachment to their cars, which is why you can still find technically efficient 25-year-old combustion cars with a mileage of around one million kilometres on Polish roads. However, the electric car is still a novelty on the Polish automotive market and therefore it is not yet possible to verify its actual durability (Brach, 2019b; Gawron & Bernatt, 2017).

Until now, it has also not been clearly established which propulsion solution is more beneficial, more 'green' or less carbon-intensive (Gawron & Bernatt, 2017). This is a debatable issue given that in most countries of the world, the predominant energy production is from fossil fuels, from which both vehicle fuels and electricity (with which cars are charged) are obtained, (Sztafrowski et al., 2021). In the Polish energy market, the share of 'green energy' is increasing year by year (Matuszewska-Janica et al., 2021), derived from renewable sources, especially solar and wind power (Gabryś, 2020; Sulich & Sołoducho-Pelc, 2021). However, fossil energy accounts for 67.76% of the share of energy generation in Poland, which translates into an energy balance in 2020 of 0.71830 Mg/MWh of carbon dioxide emissions into the atmosphere (Tauron Polska Energia S.A., 2021). Furthermore, obtaining 1 KWh used, for example, to charge an electric vehicle emits 718.30 grams of CO2 (Tauron Polska Energia S.A., 2021). Increasing demand for fuels, accompanied by declining oil production (and therefore supply), is also a problem. The entire fuel extraction process consists of many operations, each of which carries additional costs and environmental pollution. The global average CO2 emissions accompanying the extraction and processing of 1 tonne of oil are approximately 130 kg CO2 (Gavenas et al., 2015). Therefore, it is possible to calculate an average emission for 1 litre of fuel for internal combustion engines (petrol and diesel), which is 110.43 grams of CO2. Fossil fuels are not the only source of CO2, their processing or combustion produces also other pollutants.

In reports and publications as well as in the expert literature, there are numerous juxtapositions of cars with environmentally friendly solutions, but without a detailed indication of the superiority of one type of propulsion system over the other (Denis & Kuczynski, 2017; Luszczyk et al., 2021). Mostly single vehicle features are described in detail and the positive environmental impact of specific technological solutions is indicated (Gulzari et al., 2022). Also, in most cases, comparisons of electric vehicles refer to different classes and types of cars (Verma et al., 2021). In scientific publications, authors shift the focus of their analyses from environmental impact, to comparisons of fuel or energy consumption (Albatayneh et al., 2020).

The car manufacturing process is still a patent-protected corporate secret, which includes the issue of environmental damage (Pilichowska, 2020). The current difficulty is in assessing the life cycle of the plastics used in today's driving vehicles (Kotak et al., 2021). Available data only indicate fuel and/or electricity consumption. Recycling and recovery of scarce raw materials are becoming increasingly important aspects in passenger car manufacturing processes (Pietrzyk-Sokulska, 2016; Sulich & Soloducho-Pelc, 2021). In the case of lithium-ion batteries, the recovery of all used raw materials is not yet possible, and the possible extraction of some materials results in high CO2 emissions (Wojcik et al., 2017). Work on the recycling of lithium-ion batteries is still in progress (Wojcik et al., 2017). This is driven by the need to meet the latest market trends in car manufacturing. Material recovery applies to both batteries in electric cars and components in modern combustion cars (Kamińska & Pawlak, 2020). Most often, the recovery of specific raw materials and their reuse is financially beneficial (Pietrzyk-Sokulska, 2016). Despite the large pool of recovered raw materials, there is a group of components that must be treated not as waste, but as a potential object for future recycling (Sulich & Soloducho-Pelc, 2021). Therefore, the literature postulates the creation of deposits for which processing technologies have not yet been developed (Halasik & Kulczycka, 2016).

Materials and methods

The aim of the study is to compare the powertrains in SUVs of the urban type, i.e. petrol, diesel, hybrid and electric engines. The SUV type of car was chosen because of the growing demand among residents in Europe. These cars are popular because of the comfort offered (Haughton, 2012). The new car registrations report published in the first quarter of 2021 indicates that SUVs account for as much as 44% of the automotive market in European countries (JATO, 2021). Also in Poland, SUVs accounted for the largest percentage of vehicle registrations in 2021 (Polish Automotive Industry Association, 2021).

The comparative analysis includes four vehicles of a renowned SUV brand, urban type, with different drive types. The powertrains under comparison have been selected in terms of the similar parameters shown in Table 1. The vehicles (except for the hybrid version) have four-wheel drive. The information presented is based on the latest data from the manufacturer and applies to cars available in 2021.

The research method allowed several parameters to be compared among the corresponding vehicle types. A comparative analysis was chosen for reasons of transparency and possible exact comparison of the data between each other. Detailed information was taken from scientific publications, reports and manufacturer's catalogues. Based on these sources, variables describing the environmental impact of vehicle use were distinguished. Secondary data including emission tables, energy consumption and vehicle technical data were obtained from the car manufacturer. In the presentation of the results and their discussion, industry reports were used (Bieker, 2021; Canadian Association of Petroleum Producers, 2021; Polish Alternative Fuels Association, 2021; Tauron Polska Energia S.A., 2021).

Results

The SUVs under analysis have different engine versions, which is in line with the established methodology. The hybrid car has a combination of a petrol engine and an electric motor. In addition, it is the only one that does not come in a 4WD version. All the cars analysed have a power output of around 215 hp, their torque is around 373 Nm. Table 1 shows the upper limits for fuel consumption and CO2 emissions according to the WLTP test (abbreviation for *Worldwide Harmonised Light Vehicle Test Procedure*). This is a test carried out on light vehicles measuring fuel consumption and emissions. This test is used within the European Union to determine compliance with the European emissions standard, used for vehicle type-approval certificates. The values were measured under laboratory conditions and come directly from the manufacturer. Acceleration to 100 km/h is 7.2 seconds on average. Another important difference shown in Table 1, is the weight of the vehicles compared. The electric vehicle is significantly heavier than the other cars analysed.

Table 1. Selected technical data of the passenger car models compared.

Vehicle	1.	2.	3.	4.
Engine	electric	petrol and electric	petrol	diesel
Year of availability/production	2021	2021	2021	2021
Drive	4 wheels	front axle	4 wheels	4 wheels
Power (hp)	228	218	224	190
Torque (Nm)	390	350	350	400
Average fuel consumption (l/100km)	0	1,6 / 7,6	8,4	6,1
Average electricity consumption (kWh/100km)	17,5	17,5	0	0
Average CO2 emissions (g/km)	0	37 / 173	191	161
Acceleration to 100 km/h (s)	7,7	7,1	6,7	7,3
Curb weight (kg)	2105	1775	1600	1670

Source: own compilation based on manufacturer's data.

When analysing the different engine versions of vehicles, it is important to consider the area beyond average energy/fuel consumption, meaning that there are additional, hidden non-operational emissions other than those shown in Table 1. A separate category of emissions are those associated with the manufacture of the vehicle, batteries (Wojcik et al., 2017). Table 2 compares 4 engine versions of the SUV. The values shown are for the 18-year life of the vehicle, with an annual mileage of 15,000 km, i.e. approximately 270,000 km over its lifetime (Bieker, 2021). The values for manufacturing, vehicle maintenance and battery performance are from 2021 and have been averaged across the European Union and the UK (Bieker, 2021). In addition, the parameters of cars from the same manufacturer were taken into account, as well as energy generation in Poland and fuel acquisition. The data for calculating emissions at fuel/energy production were based on manufacturer parameters and values from reports.

Table 2. Indirect CO2 emissions/1km during selected processes.

Engine	electric	petrol and electric	petrol	diesel
Vehicle manufacture	27	33	30	30
Vehicle maintenance	4	5	5	7
Battery production	16	4	0	0
Fuel/energy production	125,7	70,57	9,28	6,74
Total	**172,7**	**112,57**	**44,28**	**43,74**

Source: compiled from (Bieker, 2021).

The production of the vehicle and the associated emissions settle at a similar level of around 30 grams of CO2 per kilometre travelled in each of the cases analysed. However, the electric version of the passenger car has the least complex engine. Its operation does not require as much effort as in the combustion versions. In addition, there are no operating fluids such as engine oil. The diesel unit is the most complex engine, with filters such as DPF. The requirement for refuelling with the AdBlue additive also increases the CO2 emission values.

During the 18-year life cycle of a car (not including energy/fuel consumption), an electric vehicle emits the most CO2 when emissions resulting from the production of electricity are taken into account. The hybrid car has average values in this comparison. The internal combustion engines have similar parameters, but the diesel unit has the lowest value, which corresponds to a total of 43.74 grams of CO2 emissions for each kilometre travelled. The highest value for direct CO2 emissions per kilometre travelled is observed in the petrol engine. It is also characterised by the highest fuel consumption. In the case of internal combustion engines, most of the CO2 emissions occur directly while driving.

Comparison of cars with 4 different engine versions for CO2 emissions in terms of: fuel combustion, vehicle generation, vehicle maintenance, battery production, fuel production and energy generation. In the case of the hybrid version, the data are based on a distance of 100 km travelled at maximum on the electric motor.

Table 3. Total CO2 emissions/1 km according to WLTP test

Vehicle	1.	2.	3.	4.
Engine	electric	petrol and electric	petrol	diesel
Average CO2 emissions (g/km)	0,00	81,31	191,00	161,00
Vehicle manufacture	27,00	33,00	30,00	30,00
Vehicle maintenance	4,00	5,00	5,00	7,00
Battery production	16,00	4,00	0,00	0,00
Fuel/energy production	125,70	70,57	9,28	6,74
Total	**172,70**	**193,88**	**235,28**	**204,74**

Source: own elaboration based on manufacturer's data

Vehicle 1 (electric motor) was found to be the least emitting vehicle as a result of the comparisons. The lack of direct emissions during use provides a clear advantage over other engines. Even the 'brown' energy derived mainly from fossil fuels does not affect the final ranking result. Vehicle 2, the hybrid version, takes second place with a score that is 12% worse than the electric version. Vehicle 4 ranks last in the comparison, while Vehicle 4 gets the worst score in the comparison, with up to 36% more emissions compared to the electric version.

A vehicle with an electric motor is already the most environmentally friendly solution compared to combustion versions. The values for average energy consumption and emissions are based on the WLTP test, which takes place under laboratory conditions. The actual measurements depend on a number of factors, such as weather conditions, road gradient and wind direction. Realistic emission values are not constant and results may vary under changing conditions.

Conclusion

The mobility of society is leading to a constant development of means of transport. Vehicles that look almost identical on the outside have different solutions on the inside due to the type of engine used. This paper compares the different engines of SUVs. The paper analyses the harmfulness of vehicle production processes, their operation and the sources and methods of obtaining energy factors for powering cars in Poland. The aim of the article was fulfilled through a comparative analysis of the power units of SUVs: petrol, diesel, hybrid and electric engines. The results of the research were obtained, indicating the electric drive as the least emitting solution.

The sustainability context for Polish electromobility also relates to the ways in which energy is generated in engines. The generation of electricity by coal-fired power plants or the combustion of fuels in car engines are the most harmful processes. The European Union's requirements for environmentally friendly solutions and the industry standards that are being observed thanks to widespread consumer awareness provide guidelines on how to proceed in terms of reducing exhaust emissions. In the case of individual engine versions, the standards allow for small variations in exhaust gas values by engine, but the idea of lower emissions applies to all vehicles. Differences in horsepower, weight, axle drive or vehicle performance laboratory values present challenges and directions for future interdisciplinary research. Possible directions for future research are to analyse the impact of vehicle weight on the consumption of energy factors, to analyse the life cycle of cars with different engines and to analyse driver behaviour when using a new type of propulsion system.

Sebastian Grzesiak otrzymał tytuł licencjata z logistyki na Uniwersytecie Ekonomicznym we Wrocławiu w 2023 roku i obecnie kontynuuje studia magisterskie na tym samym kierunku. Otrzymał stypendium od Ministra Edukacji i Nauki w Polsce za swoją działalność naukową (2023). Uczestniczył w wymianach Erasmus na Uniwersytecie Ekonomicznym w Warnie w Bułgarii, Uniwersytecie Techniczno-Ekonomicznym w Dreźnie w Niemczech oraz na Uniwersytecie w Ioanninie w Grecji. Jego zainteresowania badawcze skupiają się głównie na: elektromobilności, sieciach stacji ładowania oraz logistyce.
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