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Evaluation of the CO_2 emission from motor vehicles in the context of sustainable transport development

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Greenhouse gases emission is an important element in the development of the automotive industry. The unceasing trend of reducing the negative impact of vehicles on the environment is a determinant of setting directions for the improvement of their production and operation. One of the solutions in this regard are low-emission vehicles. However, this area requires continuous research and analyses, the results of which are partially presented in this article. The aim of the study was to evaluate the CO_2 emission from the selected types of vehicles as in traffic driving, measured based on the standardised type-approval tests. This method allows to easily reproduce the obtained results, reliably compare and also extend it with further tests in a completely independent manner. The CO_2 emission in the production process of the vehicle and its fuel, was also evaluated. It was assumed (research hypothesis) that CO_2 emission changes significantly with the development of production technology and the use of various vehicle power sources. Based on their own research, the authors also analysed the feasibility/reliability of the assumptions about the benefits associated with emissions, obtained by replacing the classic vehicle with the hydrogen one. They estimated the time and intensity of using a hydrogen-powered vehicle that guarantees a benefit in terms of CO_2 emissions compared to a conventional vehicle.

Key words: *greenhouse gases, hydrogen vehicles, emission measurement, directions of automotive development*

1. Introduction

The ecological effects of motorism, including the use of vehicles, are one of the most important topics in the discussion on counteracting the negative impact of transport on the environment. These effects are identified mainly with the emission of toxic exhaust components. An equally significant impact related to the entire life cycle of production, supply of fuel, operation, including use and servicing as well as the disposal, is completely omitted. For this reason, cars with alternative drives are called ecological. They are considered to be harmless to the environment and are considered an important attribute of the process to implement and expand the strategy for sustainable transport development. It is additionally supported by the forecast of depletion of the global fossil fuel resources and the related need to search for renewable and alternative energy sources. The whole thing is intensified by an aggressive marketing campaign promoting modern solutions. However, detailed life cycle emissions analysis is not a widely studied issue. The issue of ecological vehicles is undertaken in the field of scientific research within two main trends. In particular, it applies to electric vehicles, which are the most popular alternative to vehicles with internal combustion engines and the limitations of their use. They result mainly from an access to the necessary infrastructure, including energy sources (e.g. charging stations), as well as the cost of purchasing electric vehicles, which significantly exceeds the cost of purchasing traditional vehicles [19, 21, 23]. The benefits and subsidies proposed in various countries are analysed, favouring the development of vehicles with alternative drives, but above all, innovative technologies for the production of batteries, i.e. elements that are the main reason for the high price of this type of vehicles [21, 24].

These analyses are complemented by the assessment of the total cost, including production, operation, maintenance, and battery replacement [22]. The payback period for the development of new technology, depending on the vehicle class (often estimated at several to several years), is a frequent topic discussed in the available literature [21, 25, 26]. The conclusion from such studies is also the need to produce such batteries, which are characterised by lower production costs and longer service life compared to the lithium-ion and nickel-metal hydride batteries used so far. In the literature, one can also find the results of evaluations related to the future of electric drive vehicles, carried out in various regions/countries, e.g. in Turkey [15], Germany [16, 22], China [18], Great Britain, USA, Japan [21] or in the Nordic countries [17].

The second line of research presented in the literature concerns the ecological aspect of electric vehicles, including the emission of harmful substances. The lack of direct exhaust emissions means that electric cars are considered to be fully ecological vehicles. However, their negative impact on the environment is also noticeable. This impact applies in particular to the batteries and related indirect greenhouse gas emissions from their production and disposal as well as pollution from the generation of energy used for charging.

There is a widespread belief that along with the modernity of the vehicle, its greater environmental friendliness is achieved, identified primarily with reduced CO_2 emissions. Therefore, the aim of this article is not only to assess the CO_2 emissions of selected types of vehicles in traffic, measured on the basis of standardized type-approval tests.

The aim is also to evaluate CO_2 emissions in the production of the vehicle and its fuel. It was assumed that CO_2 emissions changed significantly with the development of production technology and the use of various vehicle power sources.

2. Limiting CO_2 emissions and hydrogenation of transport – the state of the problem)

Limiting emissions of gases harmful to humans, especially carbon dioxide causing the greenhouse effect, is the subject of many pro-ecological programs and initiatives. The total world CO_2 emission in the period 1990-2010 increased by approximately 49% [4]. At the same time, the European Union countries reduced CO_2 emissions by 12%. At the World Climate Conference in Paris in December 2015 (the so-called Paris Agreement), keeping the global warming below 2^oC was adopted as a target accepted by 195 countries. This meant a reduction of the cumulative carbon dioxide emissions from energy production and use, by 900 Gt by the year 2100. This is the amount that the world will emit before 2050, with the continuation of the current development trends assuming tripling the world GDP and population increase from 7.6 to 9.8 billion people [9].

Limiting global warming to below 2°C requires a reduction of CO_2 emissions by the 2050 by 85% compared to today's level and requires 160 million low-emission vehicles worldwide to be on the road by the 2030, including 80 million hybrid plug-in type vehicles and 80 million zero-emission vehicles – BEV (battery electric vehicle) and FCEV (Fuel Cell Electric Vehicles). Meanwhile, the continuation of the growing consumption of conventional fuels means that an increase in CO_2 emissions can be expected.

Limiting global warming below 2^oC applies to the period 1860-2050, and by 2015 the average temperature of the environment increased by 1.6^oC. This means that 0.4^oC remains to the upper level of global warming allowed by the 2050 [3].

In the light of forecast assumptions, global transport will double in the years 2012-2050. If the current development trends in the automotive industry were to be continued, the CO_2 emissions from transport, amounting to approx. 35 Gt CO_2 in 2012 (20% of the total industrial emissions), would double and would significantly contribute to a 60% increase in total greenhouse gas emissions, which would result in a global warming of the climate by 6^oC [3].

In the first and second decade of the 21st century, automotive concerns significantly accelerated work on ecological technological solutions. There was a massive use of direct injection and turbo charging in spark ignition engines and DPF (diesel particulate filter) in diesel vehicles, as well as downsizing power units in both of these types of power.

Electric cars and cars powered by hydrogen fuel cells have become the next stage in the development of ecological motorism.

These types of vehicles are powered by electric motors. In the case of battery-powered electric cars, the source of electricity is the battery cells, and in the case of hydrogen vehicles, the current powering the engines is generated by hydrogen oxidation. As a result of this process, electrons (which are the source of electricity supplying the vehicle) are given away, and the by-product of the reaction is water.

The International Energy Agency has indicated, in the report entitled "Technology Roadmap Hydrogen and Fuel Cells" [1], the hydrogenation of transport as one of the available energy technologies for the transformation of the energy economy. The European Commission has clearly confirmed that the development of hydrogenation is one of the key elements in achieving the goal of reducing the EU CO_2 emissions by 50-55% already in 2030. To this end, in the years 2020-2024, new electrolysers with a total capacity of at least 6 GW are to be built in the European Union, and are to produce 1 Mt of hydrogen per year. In the years 2025-2030, electrolysers with a total capacity of at least 40 GW are to be built, supported by a similar production potential of North African and Eastern European countries, primarily Ukraine. They will provide an annual hydrogen production of about 10Mt [1]. After 2030, technologies for the production and use of hydrogen are to develop on a massive scale and occupy an important position in the EU energy distribution. The total capacity of electrolysers producing hydrogen using electricity from renewable sources is to reach 500 GW in 2050 [1].

Hydrogen powered vehicles have a significant environmental advantage compared to combustion engine vehicles. They are characterised by zero CO_2 emissions during operation, as well as lower total life cycle CO_2 emissions. For hydrogen vehicles, the total life cycle CO_2 emission is 120-130 g/km (when produced from natural gas) and 60-70 g/km when using hydrogen produced from renewable energy sources [9]. It is worth emphasising that a significant part of the hydrogen used is a by-product of the production processes of the chemical industry [9].

The popularisation of FCEVs significantly reduces the costs of their production and purchase by the customer. However, with the development of technology, they consistently decrease (Table 1). According to the data at the end of 2020, there were less than 27 thousand FCEV registered in the world, most of them in the US, South Korea, and Japan [2].

Table 1. Production costs of a passenger car with a hydrogen drive in the USA in the years 2015-2050, in thousands of dollars [3]

Item/year	2015	2030	2050
vehicle cost, including	60	33.6	33.4
body cost	23.1	24.1	25.6
cost of fuel cells	30.2	4.3	3.2
hydrogen tank cost	4.3	3.1	2.8
electric battery cost	0.6	0.46	0.26
cost of the electric motor and drive	1.8	1.6	1.4
unit costs			
fuel cells (80 kW) in dollars/kW	380	54	40
battery (1.3 kW) in dollars/kW	460	350	200
hydrogen tank (6.5 kg H_2) in dollars/kW	20	14	13
hydrogen consumption in kg H_2/100 km	1.0	0.8	0.6

The increase in production and the development of hydrogen propulsion technologies is conducive to reducing costs and increasing competitiveness. The data presented in

Table 1 shows that the price of a passenger car with a hydrogen drive will decrease from the current 60 thousand dollars to 33.6 thousand dollars as early as 2030. It will practically equal the price of vehicles with other drives (with a gasoline engine – USD 30.9 thousand, with a diesel engine – USD 31.7 thousand, with a hybrid gasoline engine – USD 31.8 thousand, batteries – USD 32.8 thousand) [3]. As a consequence of the reduction of the production costs of both the hydrogen-powered vehicles themselves and the reduction of the costs of production and distribution of hydrogen, in 2030 the price of a C/D segment hydrogen vehicle should constitute only 110% of the price of an equivalent car with an internal combustion engine (compared to 300% in 2015). The total operating costs of FCEVs should equal the operating costs of conventional cars in the US in 2035-2040 [3].

Over the past ten years, the gradual reduction of the weight of platinum required in the fuel cell has made it possible to reduce the cost of produced cells by more than 50%. For large-scale production, the cost of hydrogen alone should drop from the current USD 10-15 per kg to USD 4/kg. Increase in fuel cell production from 100,000 to 500,000 units while maintaining the current technology, ensures reduction of the cost of their production to 55 USD/kW in 2030 [3].

As a consequence of the reduction of costs of individual components of hydrogen technologies, the unit cost of CO_2 emission elimination should be gradually reduced. Today, in the case of motor vehicles, these costs exceed USD 1,500/ton of CO_2 and are not competitive. It is expected that with the spread of hydrogen technologies, these costs should decrease to USD 50/ton in 2030, and to a few USD/ton in 2050. A similar cost of eliminating CO_2 emissions (USD 50 per ton) should also occur in 2030 in the industrial use of hydrogen (estimated today at $100-150/ton of CO_2). According to German sources, the initial cost of reducing CO_2 emissions by using photovoltaics for electricity production, ranging from 400 to 500 USD/ton, has already decreased to 20-70 USD/ton of CO_2 [8]. In the current situation where only about 15% of global CO_2 emission is valued, and only 5% of this emission is valued above USD 10 per ton of CO_2, the hydrogen technologies as a tool to reduce CO_2 emissions are ineffective [9]. Only reaching the level of 50 to 100 USD per ton could make hydrogen technologies a competitive method of reducing emissions of this gas. This requires a long-term policy taking into account relevant legal regulations. This policy should be co-created by all market participants, from public administration, through industry and investors to the users.

3. Author's own research

In order to confirm the hypothesis about the significant influence of the production technology and the vehicle's type of fuel supply, on the CO_2 emissions, a comparison was made of the results of authors' own research of classic drive cars. These cars were different in terms of age, usage time and technology of production of the drive unit, and as a result, the level of meeting the Euro standards. The results of authors' own research were compared with the research results available in the literature on CO_2 emissions from hydrogen vehicles resulting from their life cycle.

Subjects of the research were passenger cars with spark ignition – Ford Focus Flexifuel and Opel Insignia.

Basic technical data of these vehicles are included in Table 2. The tests were preceded by an inspection of the technical condition. A positive result was obtained, and most of all, there were no errors in the engine controllers, which proved their correct operation and lack of faults.

Table 2. Technical data of the tested vehicles

Specifications/Make	Ford	Opel
Type	Focus Flexifuel	Insignia Grand Sport
Year of manufacture	2008	2019
Engine capacity	1798 cm^3	1490 cm^3
Power	92 kW	121 kW
Vehicle category	M1	M1
Pollutants emission level	Euro 4	Euro 6
Top speed	193 km/h	210 km/h
Meter reading	130000 km	6000 km
Fuel type	gasoline	gasoline

The tests were conducted on a chassis dynamometer of the Motor Transport Institute in Warsaw. The car was placed on a one-roller test bench where the WLTC cycles were reproduced according to the WLTP procedure. The WLTP protocol (World Harmonized Vehicle Test Procedure) is used in the European Union for the type-approval of cars. It is used to evaluate the emission of toxic exhaust gas components and carbon dioxide under standardised laboratory conditions. Each vehicle's drive through such a cycle therefore follows an identical course of speed, which allows representative comparisons of exhaust emissions from individual vehicles. The exhaust gases of the tested cars are sampled by analysers and assessed in terms of the amount of individual pollutants.

The following test instruments were used during the measurements:

- AVL emission measurement system:
- CFV-CVS type CVS i60 LD S2 by AVL,
- a set of AVL AMA i60 D1-CD LE analysers equipped with two-band analysers for measuring the concentrations of the following gases:
  - carbon dioxide CO_2,
  - nitrogen oxides NO_x,
  - carbon monoxide CO,
  - hydrocarbons THC,
  - methane CH_4,
- Vaisala weather station of PTU303type for measuring temperature, humidity and air pressure during test cycles,
- a single-roller chassis dynamometer with an adjustable resistance curve by AVL-Zoellner to simulate the motion resistance of a vehicle on the road,
- LAB-EL thermohygrometer, of LB-701 type, version M with a reading panel LB-702B, for the control and registration of environmental conditions during vehicle conditioning prior to testing.

The measurements were carried out at a constant value of temperature (23±1°C) and air humidity (50±5%). Before the measurements were taken, the vehicles were conditioned for 12 hours. The coefficients of the resistance curve of the chassis dynamometer were determined. Total and average CO_2 emission was measured.

4. Test results

In accordance with the adopted test algorithm, first the coefficient of the resistance curve of the chassis dynamometer was determined for the tested vehicles (Table 3). These coefficients make it possible to write the square trinomial function describing the motion resistance of a given vehicle on the road, which is then entered into the computer controlling the chassis dynamometer. The electric motors of its rollers, on which the tested car is placed, simulate the motion resistance of the vehicle in a manner as close as possible to the real one occurring in the road conditions.

Table 3. Coefficients of the chassis dynamometer's motion resistance curve

	Ford Focus Flexifuel	Opel Insignia
RW [kg]	1330	1607
F0 [N]	62.98	15.840
F1 [Ns/m]	3.2746	1.4658
F2 [Ns^2/m^2]	0.40109	0.34366

Next, the total CO_2 emission of the vehicles tested was measured in the WLTC cycles. The results obtained are presented in Table 4.

Table 4. CO_2 emission from the vehicle in the WLTC cycle [g/km]

Cycle number/ vehicle	1	2	3	4	5	Average in the test [g/km]
Opel Insignia	153.31	155.61	152.94	153.36	153.86	153.82
Ford Focus Flexifuel	159.18	160.68	161.46	158.39	159.64	159.87

The research shows that the Euro 6 car (Opel Insignia) emits 154 gCO_2/km in the WLTC test, and the 2006 Ford Focus Flexifuel, which meets the Euro 4 standard, emits 160 gCO_2/km.

Table 5 shows the average CO_2 emissions (in g/km) for individual vehicles in the road traffic. The emissions values for combustion engine vehicles are the values obtained from measurements from the exhaust systems of these vehicles over the WLTC. The exact determination of the value of CO_2 emissions in the refining process is difficult because it depends on many factors, such as the refinery itself or the availability of the deposit [27]. The research assumed that the CO_2 emission generated in the petrol refining process amounts to approximately 30% of the CO_2 emission value during fuel combustion in the engine. Based on the assumption, the values of fuel production emissions for cars with a combustion engine were estimated translated into g/km. Since, in the case of hydrogen-powered vehicles, CO_2 emissions in the process of fuel combustion do not occur, Table 5 shows the emissions associated with hydrogen production, taking into account its various methods.

The production of 1 kg of hydrogen from electrolysis requires 0.18 kg of CO_2 and 54 kWh. On the other hand, the production of 1 kg of hydrogen from natural gas reforming emits 10.6 kg of CO_2. Knowing the emission cost of producing 1 kg of hydrogen, the emission in g/km was calculated. The Hyundai Nexo, tested in the WLTC test, was characterised by the hydrogen consumption of 9.5 g/km. This corresponds to emissions of 1.71 g/km CO_2 for the fuel obtained as a result of electrolysis and 100.7 g/km CO_2 for the fuel obtained as a result of reforming.

Table 5. Average CO_2 emissions from the tested cars

Vehicle	Average CO_2 emission in the road traffic [g/km]	CO_2 emission related to the fuel production [g/km]	Total [g/km]
Ford Focus Flexifuel	160	48	208
Opel Insignia	154	46	200
Hyundai Nexo (taking into account the emission costs of hydrogen production in the electrolysis process)	0	1.71 14.5 – including compression and transport	1.71 14.5 – including compression and transport
Hyundai Nexo (taking into account the emission costs of hydrogen production in the reforming process)	0	100.7 113.49 – including compression and transport	100.7 113.4 – including compression and transport

It should be emphasised that the use of hydrogen-powered vehicles is also associated with additional CO_2 emissions. It results from the need to compress hydrogen, transport it from the production site, and manufacture of a hydrogen fuel tank.

To compress hydrogen from 30 to 1000 bar requires 2.7 kWh per kilogram of hydrogen. For the countries with a green energy mix, hydrogen compression requires 421 gCO_2/kWh. This is the data adopted for the German energy mix in 2020-2030. In the case of Poland, hydrogen compression would be associated with higher CO_2 emissions, which results from the specificity of the Polish energy mix. Transporting hydrogen over a distance of 200 km results in an additional 0.21 kg of CO_2 for 1 kg of hydrogen. Therefore, assuming the average distance of hydrogen transport from the production site to the refuelling station of 200 km, CO_2 emission resulting from fuel compression at the level of 1.137 kg per 1 kg of hydrogen (2.7 kWh per 1 kg of hydrogen), the total emission in the electrolysis process will be 1.53 kg of CO_2 and in the reforming process, 11.95 kg of CO_2 per kilogram of hydrogen fuel produced. This gives CO_2 consumption of 14.54 g/km for electrolysis and 113.49 g/km for reforming.

An undertaking that entails significant CO_2 emission is also the manufacture of the tank. In a typical production scenario, this is 27.6 kg of CO_2 for 1 kg hydrogen tank. In the best scenarios, the emission is 20 kg of CO_2, and in the worst case even 39 kg of CO_2 for 1 kg tank [5]. Therefore, assuming the average emission in the production of the hydrogen tank of the Hyundai Nexo car, it amounts to 154.56 kg of CO_2. In addition, the production of FCEVs requires rare earth raw materials – especially platinum, the demand of which has been determined at 0.43 g per 1 kW of a fuel cell power.

5. Discussion of the results

First part of the discussion concerns internal combustion engine-powered vehicles. Two such vehicles with similar engine power and weight were tested. It turns out that the car complying with Euro 6 standard emits 154 g/km of CO_2 in the WLTC test, and the 2006 Euro 4 Ford Focus Flexifuel emits 160 g/km of CO_2 (Table 4). Thus, according to the results of the tests conducted, the difference in CO_2 emissions per 1 km between the tested vehicles is only 6 grams. In the case of conventional vehicles, the ecological profit from the purchase and use of a modern vehicle that meets the Euro 6 emission standard (taking into account the emission costs of its production) and the replacement of an older car that complies with the Euro 4 standard would appear only if the new vehicle had driven around 700,000 kilometres.

In the case of hydrogen vehicles, the assessment of the CO_2 emission is not related to the production of carbon dioxide in traffic, since in this case the combustion product of the fuel is only water in addition to the energy. This allows hydrogen vehicles to be universally considered emission-free.

However, the production of hydrogen fuel is not a zero-emission process. CO_2 is produced during the production process itself, as well as during the compression and transport of hydrogen. Taking into account the calculations presented in the article and the assumption that the event of replacing the used car that meets the Euro 6 emission standard with a hydrogen-powered vehicle, 5.6 tons of CO_2 will be emitted. The emission benefit resulting from reduced emissions during operation will be achieved after driving approx. 30,000 km for the fuel produced as a result of electrolysis. However, in the case of fuel production in the reforming process – after approx. 65,000 km.

6. Conclusions

Currently manufactured passenger cars are characterised by lower CO_2 emissions than cars produced 10-15 years ago, but the differences are not large. The cumulative value of CO_2 emissions during the production of a VW Golf car from 1990 was 4.1 tons, while its equivalent in 2000 was 4300 kg of CO_2 for vehicle [6]. Currently, it is assumed that the CO_2 emission related to the production of a modern B/C class car amounts to an average of 5600 kg of CO_2 for vehicle [10].

The increase in CO_2 emissions during production is mainly due to material changes that have taken place in the last two decades. There was a significant increase in the consumption of aluminium and its alloys and an increase in the share of plastics and rubber in subsequent models of passenger cars introduced into the production. This increase took place at the expense of a decrease in the share of steel, cast steel and cast iron. These changes took place to varying degrees, on vehicles of all makes and classes [7].

The results of the tests carried out showed that the difference in CO_2 road emissions between the tested vehicles is only 6 g/km. Although the Opel Insignia is about 100 kg heavier but this proves that the ecological profit in terms of CO_2 emissions from the purchase and use of a vehicle that meets the Euro 6 emission standard is not significant. Therefore, for a wide group of passenger car users, who drive them several thousand kilometers a year, a more ecological solution will be to use a previously owned car while maintaining its good technical condition. Replacing it with a new vehicle would result in additional emissions of several tons of carbon dioxide into the atmosphere. The paper does not discuss the differences in the emission of exhaust toxic components, which are obviously lower for Euro 6 vehicles.

When compared with a hydrogen vehicle, the absence of emissions in operation is compensated for during the production and compression of hydrogen. The result is that a vehicle that is generally considered emission-free it is not in fact. However, these emissions are much lower than those of conventional vehicles. This, in turn, means that the balancing of CO_2 emissions during production, in the operation process, can be achieved after travelling several tens of thousands of km.

The article presents and discusses a number of factors influencing the amount of CO_2 emission during the production of vehicles and their components, as well as the dependence of emissions on the production method and type of fuel. The life cycle emissions for a modern hydrogen car and for conventional vehicles meeting various emission standards were compared, and the differences were demonstrated, thus justifying the adopted research hypothesis and the objective of this study.

Nomenclature

GDP	global gross domestic product
BEV	battery electric vehicle
FCEV	fuel cell electric vehicle
WLTP	World Harmonized Vehicle Test Procedure
CFV-CVS	emission measuring system
AMA i60	emission measuring system
LAB-EL	thermohygrometer
RW	set vehicle mass
$F_{0,1,2}$	curve coefficients

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