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Aleksander Sładkowski *Editor*

Ecology in Transport: Problems and Solutions

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Ecology in Transport: Problems and Solutions

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Preface

Very often, the inhabitants of planet Earth in their daily lives do not realize the importance that transport takes in our lives. Nevertheless, if you do not take more distant time periods, you can compare how much time for traveler took a trip from Europe to Australia 200 years ago. It usually took several months. These days are a few hours. The reasons for this are understandable—these are the achievements of science aimed at the development of new means of transport, the related improvement of transport infrastructure, as well as the development of entire sectors of the economy that are involved in the development, production, and operation of means of transport.

Ultimately, although this is not so obvious, the development of transport affects the change in the political map of the world. An example is the creation of the most powerful state at present, which is the USA. This state was founded by immigrants from various European countries. But could they carry out this relocation, if there weren't the necessary means of transport for this?

The ambitious project of China, which was called "One Belt, One Road"[1] is currently under active discussion. The project is based on the delivery of goods using various means of transport. But in reality, the essence of this project is much wider. It implies a global change in the economies of countries that are in the zone of its implementation.

There are many more such general considerations, but it should be noted that the development of transport, with all its positive impact on the fate of mankind, also carries certain threats, the main of which is its negative impact on the environment. There are many factors that are caused by transport and which affect the environment. Various emissions to the atmosphere and water, thermal effects, noise and

[1]Hofman B (2015) China's One Belt One Road Initiative: What we know thus far. URL: http://blogs.worldbank.org/eastasiapacific/china-one-belt-one-road-initiative-what-we-know-thus-far.

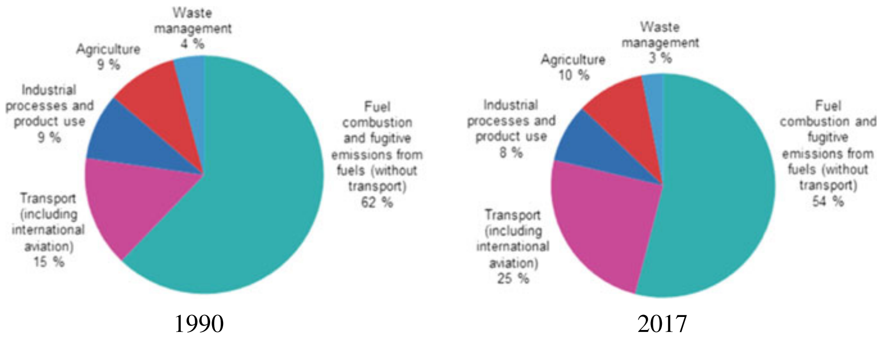

Fig. 1 Greenhouse gas emissions, by source sector, EU-28, 1990 and 2017 (percentage of total). *Source* Eurostat (env_air_gge), European Environment Agency [Greenhouse gas emission statistics—emission inventories. Statistics Explained (2019) URL: https://ec.europa.eu/eurostat/statistics-explained/pdfscache/1180.pdf]

vibrations, as well as a number of others can be noted. At present, one can no longer ignore the threat that the greenhouse effect poses to humanity. Residents of Europe have already quite felt the climatic changes that are a consequence of this effect. But if the consequences here are not yet catastrophic, then fires in the vast territories of Australia at the end of 2019 can be talked about as a global catastrophe.

The following greenhouse gas comparison charts show how significant the impact of transport is on this issue. At the same time, it can be clearly seen that over the past 27 years, the amount of such emissions related to transport has increased by 10%. However, these charts do not fully reflect the impact of transport, since they only take into account direct emissions. However, if the source of energy, for example, for an electric locomotive, is the current generated at a power plant, then a pure source of energy is far from always used for its production. At thermal power plants, the burning of coal, gas, or fuel oil also emits greenhouse gases, which means that ultimately the environmental impact of transport is even greater (Fig. 1).

Thus, it makes no further sense to prove that the solution of environmental problems related to transport is an urgent problem of modern science. Moreover, different countries have a significantly different environmental situation and a significantly different approach to solving environmental problems. Nevertheless, when such problems concern the whole of humanity, compromises can be found. The final document adopted at the conference (COP24) in Katowice in December 2018, which was attended by almost 14,000 delegates from 195 countries, is an example.

At this conference, special attention was paid to transport. For example, the problem of the development of e-mobility was considered. Poland and UK proposed the adoption of a joint declaration,[2] which was ultimately signed by representatives of 1200 leading companies from 38 countries.[3]

But is electric transport completely eco-friendly? After all, as mentioned above, the main issue is the source of energy necessary for the movement of the vehicle. And if the generation of primary energy is simply transferred from the combustion of fuel directly in a car running on hydrogen fuel, or in an electric locomotive that receives energy from a trolley line, to the generation of energy at a power plant, then the environmental problem is simply transferred from one place to another. Thus, the environmental problems of transport should be considered comprehensively, taking into account the experience of various countries.

This task was undertaken by the editor of this publication, inviting colleagues from different countries to share their experience in developing means of transport and transport infrastructure in order to solve environmental problems for each specific region. The team of authors of this monothematic monograph consists of scientists from Lithuania, Poland, Ukraine, Bulgaria, Slovakia, Russia, and Latvia. The order of countries in this list is related to the topics of the respective chapters, which were written by representatives of these countries.

The first chapter of the book was written by Lithuanian scientists who concentrated their research on the use of fuels, which, when burned, emit less CO_2. Alternative fuels, biofuels, and fuels based on various gases are considered, and comparisons are made with electric vehicles. It also considers the use of hydrogen as an additive to various gaseous or liquid fuels, as well as the use of pure hydrogen.

The next chapter of Polish scientists considers more specific gas mixtures: hydrogen (H_2), hydrogen–methane mixtures (HCNG), and dimethyl ether (DME). It also discusses the more efficient use of gaseous fuels in order to increase their efficiency and reduce harmful emissions.

The use of biofuels as an energy source for vehicles is considered in the third chapter of Ukrainian and Polish scientists. At the same time, all interrelated processes are considered, starting from the production of this type of fuel, taking into account environmental aspects at all stages.

In the fourth chapter, Bulgarian scientists concentrated on analyzing the operation of electric cars or hybrid cars. As an energy source can be used electric batteries, gas fuel, including hydrogen or traditional fuels. The use of bicycles with an electric motor is also considered. The comparison of greenhouse gas emissions for the countries of the European Union is described.

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[2]Driving Change Together—Katowice Partnership for E-Mobility (2018) URL: https://cop24.gov.pl/fileadmin/user_upload/files/Driving_Change_Together_Partnership.pdf.

[3]Thirty-eight Countries, 1200 Companies Join E-Mobility Partnership, COP Presidency Announces Just Transition Declaration (2018) URL: https://sdg.iisd.org/news/38-countries-1200-companies-join-e-mobility-partnership-cop-presidency-announces-just-transition-declaration/.

The next chapter, despite the fact that it was written by scientists from another country (Slovakia), could be called a natural continuation of the previous chapter, since it considers the legal aspects of European environmental policy aimed at reducing harmful emissions from the use of vehicles and primarily greenhouse gases. The chapter discusses aspects of the impact of European standards on environmental protection.

If the previous chapters were primarily aimed at solving the environmental problem for an individual vehicle, this chapter, written by scientists from Russia and Poland, considers the problem more broadly, studying the supply chain of goods taking into account environmental problems. It is not surprising, therefore, that the term “green logistics,” which has recently become generally accepted, is widely used by the authors.

The environmental problems associated with the use of transport are primarily felt by residents of large agglomerations. At the same time, the use of new solutions for the development of transport networks can help improve the situation. The Polish authors of this chapter, based on surveys of a large number of specialists, analyze the environmental problems of implementing the concept of a “smart city.”

The eighth chapter, co-written by scientists from Bulgaria and Poland, examines the various environmental problems of the urban economy. Their solution can be the use of both new means of transport, including those developed by students, or river ships using solar energy, and the development of optimal routes for urban transport.

The last chapter, presented by Latvian experts, is somewhat different from the previous ones, since it considers a slightly different type of environmental pollution. Such pollution is noise and vibrations that are generated by the movement of vehicles. The authors analyzed the movement of rail transport from the point of view of the possibility of applying the EU method of noise measuring for local railways.

Obviously, in the brief summaries given above, far from all the aspects described in the corresponding chapters of this monograph are described. I would also like to note that Springer Publishing House pays great attention to scientific research in the field of transport. This monograph, published under my editorship, is the fifth edition that is published in this publishing house. Environmental aspects related to transport, albeit to a lesser extent, have already been considered in previous books, some of which can also be recommended to readers interested in environmental issues in transport.[4, 5, 6]

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[4]Sładkowski A (ed.) (2017) Rail transport—systems approach. Studies in systems, decision and control 87. Cham: Springer. ISBN 978-3-319-51502-1.

[5]Sładkowski A (ed.) (2018) Transport systems and delivery of cargo on East—West routes. Studies in systems, decision and control 155. Cham: Springer. 2018. ISBN 978-3-319-78294-2.

[6]Sładkowski A (ed.) (2020) Modelling of the interaction of the different vehicles and various transport modes. Lecture notes in intelligent transportation and infrastructure. Cham: Springer Nature Switzerland AG. ISBN 978-3-030-11511-1.

In conclusion, I would like to wish for readers, who are interested in environmental issues, to receive new useful information that may be useful for practical use in the field of designing vehicles, developing transport systems, creating transport infrastructure, logistics for delivering goods, and providing other transport services. Obviously, scientists, teachers, and students can and should be readers of this book. But despite the scientific nature of the book and its rather specialized orientation, it can also be recommended for a wider circle of readers who are interested in environmental aspects in the transport industry and the achievements of modern science in various countries.

Katowice, Poland Aleksander Sładkowski

Contents

Alternative Carbonless Fuels for Internal Combustion Engines of Vehicles 1
Gintautas Bureika, Jonas Matijošius and Alfredas Rimkus

The Gaseous Fuels Towards Contemporary Economic and Ecological Challenges 51
Marek Flekiewicz, Grzegorz Kubica and Paweł Fabiś

Environmental Aspects of the Production and Use of Biofuels in Transport 115
Myroslav Panchuk, Sviatoslav Kryshtopa, Aleksander Sładkowski and Andrii Panchuk

Energy Efficiency and Ecological Impact of the Vehicles 169
Ivan Evtimov, Rosen Ivanov, Hristo Stanchev, Georgi Kadikyanov, Gergana Staneva and Milen Sapundzhiev

The Impact of Road Transport on the Environment 251
Jozef Gnap, Branislav Šarkan, Vladimír Konečný and Tomáš Skrúcaný

Logistic Flow Control System in Green Supply Chains 311
Nikita Osintsev, Aleksandr Rakhmangulov, Aleksander Sładkowski and Natalja Dyorina

The Paradigm of Sustainable Transport and Mobility in Modern Transport Policy—A Case Study of the Mobility of the Creative Class in Poland 381
Barbara Kos, Grzegorz Krawczyk and Robert Tomanek

Research on the State of Urban Passenger Mobility in Bulgaria and Prospects for Using Low Carbon Energy for Transport 441
Velizara Pencheva, Asen Asenov, Ivan Georgiev and Aleksander Sładkowski

Environment Safety Improving Due to Railway Noise Management Decreasing of RMR Method Adaptation 505
Mareks Mezitis, Guntis Strautmanis, Andrejs Baranovskis and Ruslans Muhitovs

Alternative Carbonless Fuels for Internal Combustion Engines of Vehicles

Gintautas Bureika, Jonas Matijošius and Alfredas Rimkus

Abstract The problematics of decarbonisation in road transport sector is considered in this chapter. The impact of growing motor vehicle fleet on pollutant by carbon dioxide (CO_2) gases of atmosphere is analysed. The detail analysis of purposeful restriction of permissible level of comparative amount CO_2 in car exhaust gases in EU to control the total CO_2 emission in road transport sector is presented. The urgent demand to use carbonless fuel additives to stop the growth of total amount of CO_2 emission during vehicle traction transient process "from heat power to electric power" is clarified. The introduction of electric cars by itself does not solve the problem of decarbonisation, since it is necessary to assess how electricity is produced, whether from renewable sources or by burning fossil fuel. The objective reasons for the delay in the widespread implementation of electric vehicles are investigated: the distance of one battery charge dissatisfied with drivers, an underdeveloped network of battery recharging stations, problems with the capacity and overloads of state-run electric networks, aspects of determination of time for recharging private cars, and insufficient government support measures. The main characteristics of the integrity of biofuel production and use and the continuous biofuel supply chain are described. Direct and indirect the 4th generation biofuel production processes, photo-fermentation and gaseous reversible reaction for hydrogen production are described. Using of hydrogen as carbonless fuel for internal combustion engines (ICE) slightly improves the burning processes of ICE combustible mixture and this decreases on ICE emission harmfulness. The undisputed advantages of hydrogen as ICE fuel additive encourages the development of hydrogen re-fulling infrastructure. Gained results of performed

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stand tests to define the efficiency of ICE and exhaust gases toxicity using Brown's gas (HHO) are described. Finally, basic conclusions are given.

Keywords Transport sector · Internal combustion engines · Greenhouse effect · CO_2 emissions · Carbonless fuel · Biofuels · Electro mobility · Brown's gas (HHO)

1 Growing Contribution of Automotive Transport Sector on Worldwide Greenhouse Gases Formation

The persistent growth of the global economy is a direct cause of the ever-increasing consumption of fossil fuels (oil, gas), which increases the planet's global warming and the potential irreversible effects of natural destruction. Due to mankind's active engineering activities, that is, since the Industrial Revolution, the concentration of CO_2 in the Earth's atmosphere has increased 1.48 times: from 280 ppm in 1750 to 415 ppm in 2019. Global warming has led to an incredibly rapid melting of glaciers and a dramatic increase in natural disasters, such as long-term rains, massive floods, hurricanes, etc. Total global emissions of CO_2 in 2015 were 32.3 Gt, while 7.8 Gt is attributable to the transport sector [1].

Unceasing growth of world population and economy, especially in East Asia countries India and China, causes to remarkable increasing of road vehicle fleet. Currently, the most automotive regions in the world, the EU with 239 million passenger cars and 35 million lorries on the road, have the greatest responsibility [2]. The 2nd largest country is US, which has up to 230 million road vehicle fleet. The whole vehicle fleet in these countries will grow over the next 20 years up to 30%. However, in rapidly developing economies, experts forecasting a dramatic growth of vehicle fleet in following countries or regions. Number of passenger cars: India—6.0 times, China—2.2 times, Middle Eastern countries—1.6 times, Far East—1.2 times, though number of lorries: India—2.8 times, China—0.9 times, Middle Eastern countries—1.4 times (Figs. 1 and 2).

In this way, in 2030 on roads of the world will drive about 1.7 billion various types of motor vehicles and almost 0.9 billion motorcycles. Considering the contribution of internal combustion engine (thereafter—ICE) of motor vehicles emissions to the Green House Gases (thereafter—GHG) formation, it is quite realistic to predict that already in 2030, this influence on the atmosphere will be disastrous. As sequences of this is high demand of fossil fuels, especially when the improvement in the standard of people living is getting higher and it results in the total energy consumption [3, 4].

Humankind's, or rather civilization's, the immediate strategy is significantly to decrease fossil fuels (oil) consumption, as a radical reduction way of GHG, especially CO_2 [5]. The GHG emissions from the European transport sector currently represent approximately ¼ of total GHG emissions from the EU. Nevertheless, passenger cars and light duty vehicles are dominated—53%, whilst those from heavy duty vehicles and buses are 19% and those from maritime transport ~14% and from aviation ~14% [6, 7]. Finally, road transport currently produces 17% of the EU's total GHG missions.

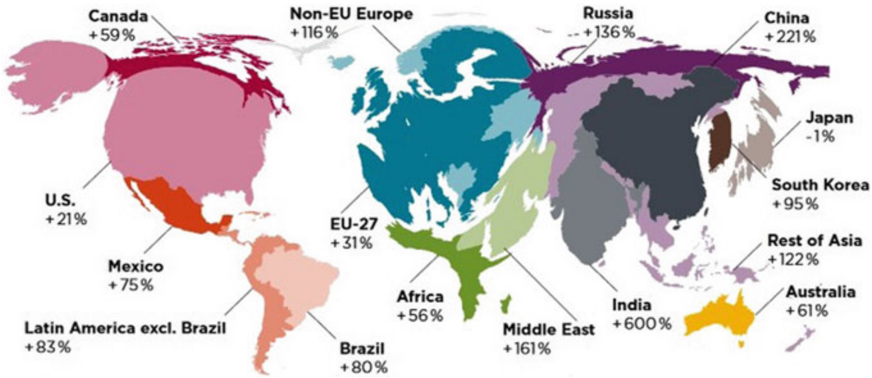

Fig. 1 Prognosis of alteration of worldwide passenger car fleet from 2010 since 2030 [2]

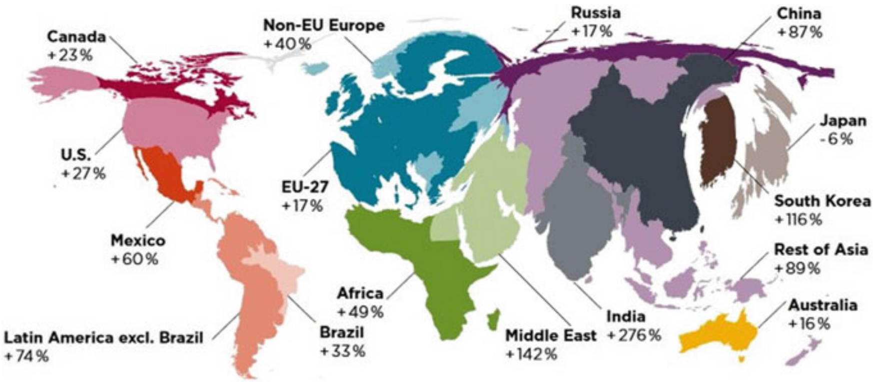

Fig. 2 Prognosis of alteration of worldwide lorry fleet from 2010 since 2030 [2]

It is noteworthy that CO_2 gas has the lowest impact of all GHG-inducing, but its emissions are unconditionally dominant. The agreement reached at the Paris International Climate Conference in 2015 set the goal to ensure that global temperature increase does not exceed 2 °C compared to pre-industrial levels. The EU Strategy on Adaptation to Climate Change was adopted in 2013, which calls on Member States to take timely action to respond to changes in the warming climate. The EU greenhouse gas trends, projections and management objectives are presented in Fig. 3.

In 2015, the transport sector accounted for about 25% of total CO_2 emissions in the EU. It should be noted that since 2014 transport emissions have started to increase again. As a result, this sector has become one of the key challenges for the EU's overall goals of reducing its dependence on fossil fuels. Greenhouse gas emissions in the EU's transport sector are shown in Fig. 4.

The majority of these emissions in the EU are from private cars, while the "contribution" of commercial transport (lorries and buses) accounts for only about 7% of all

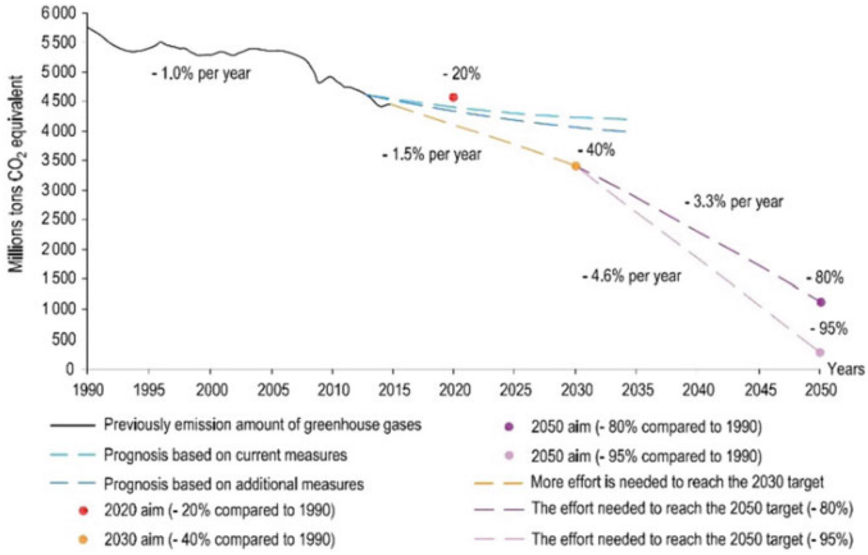

Fig. 3 GHG amount altering tendencies, prognosis and goals of activities in EU countries in 1990–2050 [8]

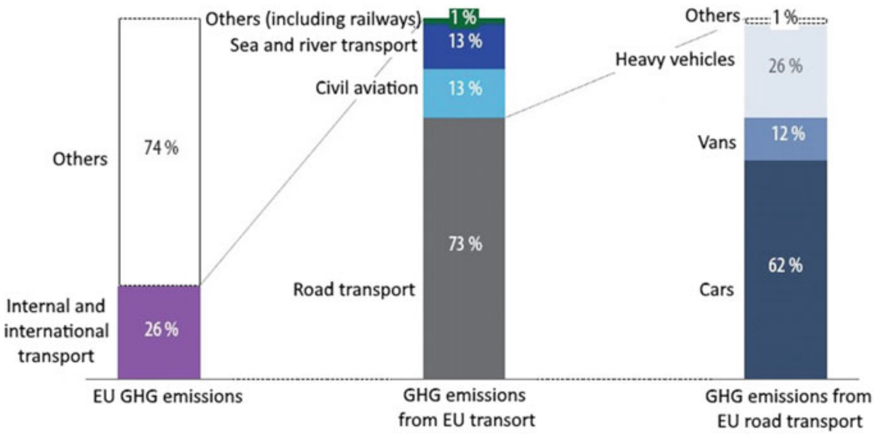

Fig. 4 GHG emissions in the EU's transport sector in 2015 [9]

road transport emissions. The aim of EU policies is to achieve "zero CO_2 emissions" for land transport by 2050, i.e., to switch completely to electric vehicles. However, electric cars are not a "panacea" that would in itself solve the issue of CO_2 emissions. It is necessary to evaluate the way in which electricity is produced. Namely, what is the method of generating electricity: hydropower plants, nuclear power plants, thermal power plants or renewable energy sources (solar photovoltaic cells, power plants, etc.). The main sources of electricity and heat generation in the EU and Member States in 2015 are shown in Fig. 5. As we can see, In Poland and Czech Republic most of the electricity is generated by burning coal, meanwhile in Estonia—by burning shales. Thus, the widespread use of electric vehicles in these countries would not at all improve the CO_2 emissions situation. Assessing the level of decarbonisation (atmospheric pollution) in major cities would improve the ecological situation, but on a national (global) scale, it is unlikely.

Therefore, it is necessary to seek that not only transport but also the power generation economy would shift to clean/renewable energy sources, i.e., significantly reduce and/or to abandon the use of electricity produced non-organically ("in the traditional way"). The indisputable effect of the use of energy from renewable sources is well illustrated by the diagram in Fig. 6.

Unfortunately, nowadays, the vast majority of motor vehicles (engines) are powered by fossil fuels, i.e., by burning hydrocarbons—petroleum products or gas. The end product of this combustion process, apart from other emissions, is always CO_2 gas. Their content is directly proportional to the amount of hydrocarbon fuel burned.

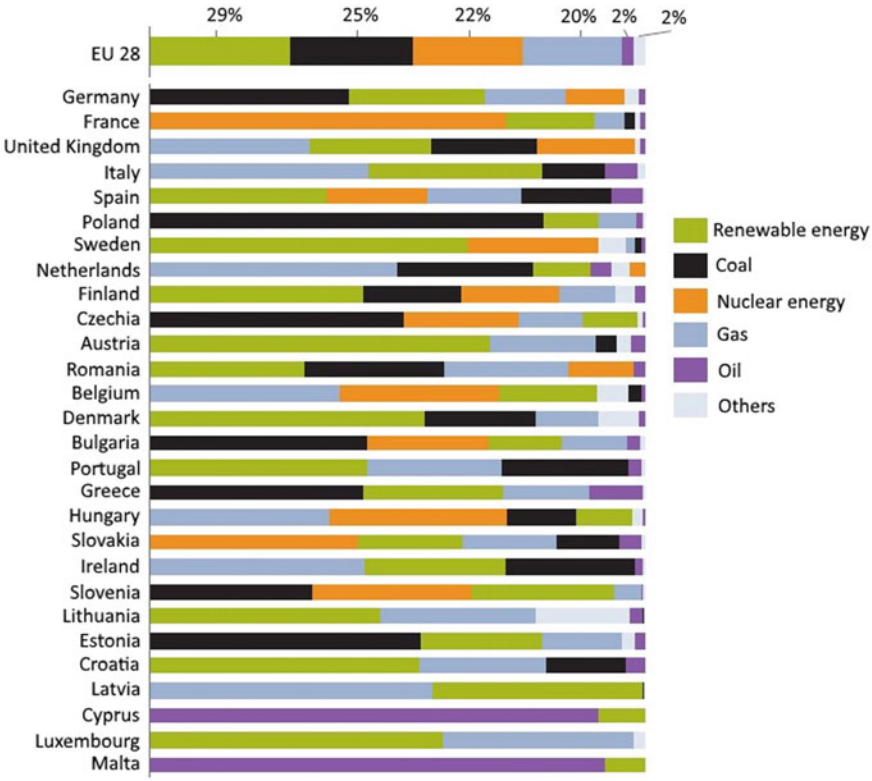

Fig. 5 Main sources of electricity and heat producing in the EU Member States in 2015 [10]

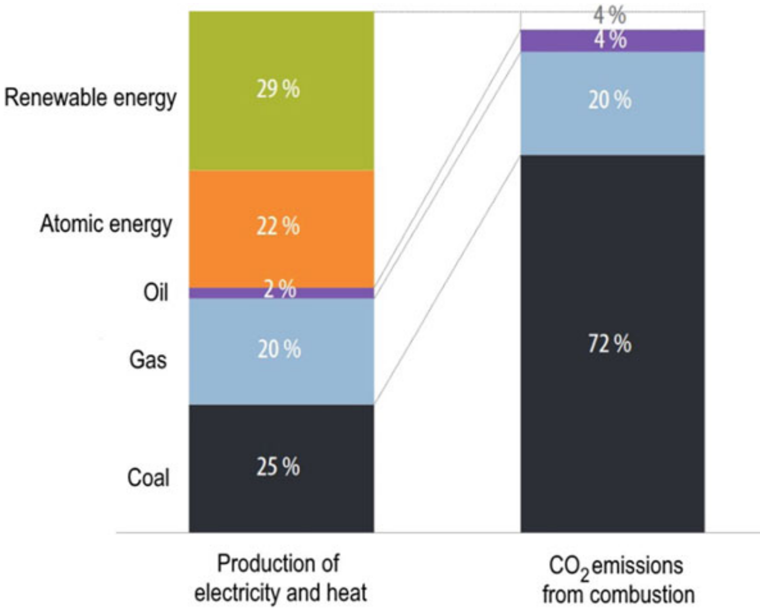

Fig. 6 Electricity and heat production as well as CO_2 emissions from different energy sources in 22 EU Member States produced in 2015 [10]

In practice, alternative fuels are used for the partial replacement of fossil fuels: hydrogen, alcohol, oils, synthetic fuels and so on [11]. Alternative fuels are fuels or energy sources which, while supplying energy for transport, at least partially replace fossil-fuel-derived fuels and which can contribute to the decarbonisation of transport and improve the environmental performance of the transport sector.

Alternative fuels (energy resources) include, inter alia:

(1) electricity;
(2) hydrogen;
(3) biofuels as defined in Article 2(i) of EU Directive 2009/28/EC;
(4) synthetic fuels and paraffinic fuels;
(5) gaseous (compressed natural gas—CNG) and liquefied (liquefied natural gas—LNG) natural gas including bio-methane;
(6) liquefied petroleum gas (LPG).

It should be noted that biofuels also contain carbon and "produce" the same CO_2 gas when burned. Another negative aspect of biofuel use is the burning of vegetation, which in the process of photosynthesis decomposes CO_2 gas (see Fig. 7).

By burning biofuels, we get the "double effect" of damaging nature: we burn fuel from vegetation (the "lungs" of the planet) and at the same time increase the concentration of CO_2 gas in the atmosphere. Another negative aspect of the use of biofuels is that the agricultural sector allocates its farmland (crop) areas and labour resources for plants intended for non-food industry but for the production of ICE fuel.

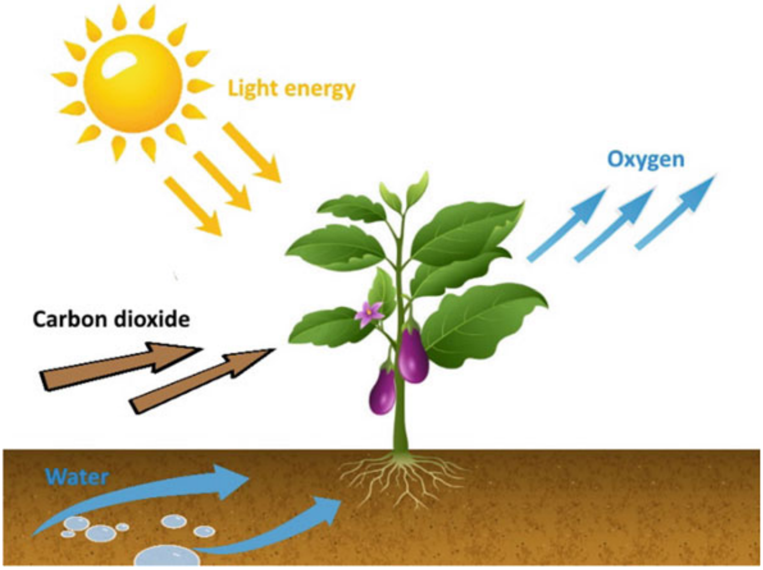

Fig. 7 The use of carbon dioxide in the process of photosynthesis

Biofuels account for about 70% of renewable energy used in the transport sector [10]. They are made from biomass, such as biodegradable agricultural and forestry products, household or industrial waste. In general, biofuels have a lower GHG emission potential than fossil fuels. CO_2 emissions from biofuel combustion have been "captured" from the atmosphere by growing biofuel source materials (plants), while the oil that would otherwise be burned remains "safely" in the depth of the Earth.

2 Socio-economical Aspects and Regulations of Substantial Reduction of Transport Pollution

From a technical point of view, efficient energy use means lower energy costs while maintaining the same level of economic activity and/or service volume. Energy saving is a broader social concept that includes reducing usage by changing the behaviour of people (consumers) or limiting their economic activities. In essence, the two concepts are difficult to distinguish and they are often used interchangeably in the EC Communication [12]. Car designers and engineers strive to save energy only through energy efficiency. This is in line with the principles of decarbonisation, which aim to significantly reduce CO_2 emissions from ICE,s and at the same time even increase the efficiency of ICEs [13].

Today mankind's economic activities and ever-increasing living standards are unthinkable and impossible without the transport sector. Transport is a strategic sector of the EU economy, with transport services accounting for around 5% of total EU value added and 5.2% (or around 11 million) of total jobs in 2016. It has a direct impact on the daily lives of all EU citizens and ensures the flow of goods to consumers from more than 11 million EU producers in various fields. A stable and efficient transport system is the basis for the integration of EU countries. Balanced, sustainable and fully interconnected transport networks are a prerequisite for the creation and proper functioning of the European entire market.

The road transport sector will continue to dominate in our daily round for many years to come because of its unique ability to carry goods and/or passengers "door-to-door". Road transport in the EU accounts for the bulk of passenger and freight transport by volume. Road transport covers approximately about 49% of all freight transport activity in the EU, followed by sea and rail transport—32% and 11% respectively [14]. Traveling by private car is the main means of transport for people, accounting for approximately 71% of all passenger-kilometre transport activity, followed by transport (aviation), buses and coaches and rail transport—about 10%, 8% and 7% respectively [15].

The European standard EN 16258 "Methodology for calculation and declaration of energy consumption and greenhouse gas emissions of transport services" requires the calculation and declaration of energy consumption and GHG emissions of transport services on whole energy utilisation process. EWT methodology [16] provides two process steps and the sum of both are distinguished

1. Final energy consumption and vehicle emissions, i.e. operation. "Tank-to-Wheels" (TTW).
2. Upstream energy consumption and upstream emissions, i.e. energy provision, production and distribution. "Well-to-Tank" (WTT).
3. Total energy consumption and total emissions: Sum of operation and up-stream figures. "Well-to-Wheels" (WTW).

In this context attention should be paid to fact that WTW energy consumption is also very often referred to as primary energy consumption, TTW energy consumption as final energy consumption. Thus, the results for energy consumption and GHG emissions calculated with ETW are in complete compliance with above mentioned standard EN16258:2012. All emissions directly caused by the operation of vehicles and the final energy consumption are taken into account. Additionally, all emissions and the energy consumption of the generation of final energy (fuels electricity) are included. Energy utilisation and vehicle operation system boundaries are shown in Fig. 8.

Thus, when searching for alternative energy sources and ways of using them in road transport, it is not only the final energy consumption (TTW) that needs to be considered, but the holistic approach and the whole life cycle of energy use (WTW) must be considered, i.e., from energy extraction, storage, distribution to end use for traction (wheel interaction with road).

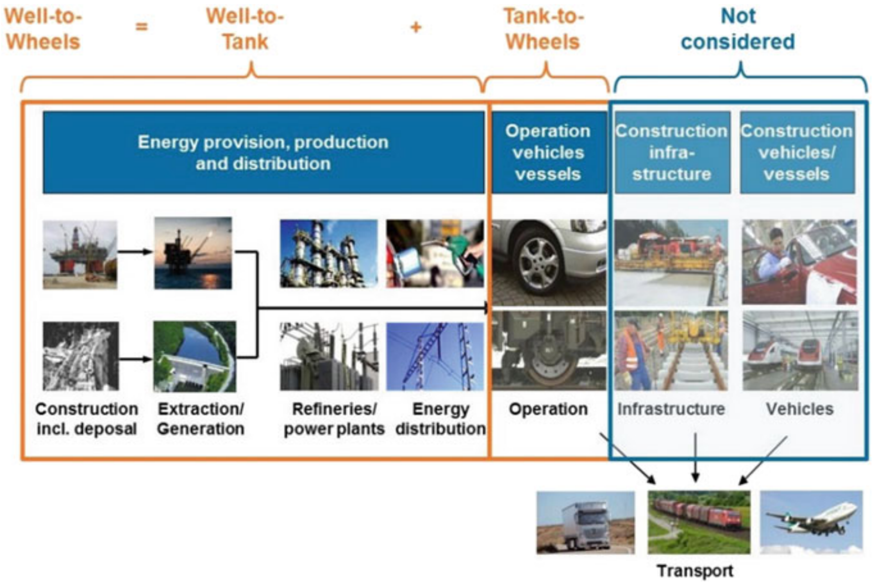

Fig. 8 Energy utilisation and vehicle operation system boundaries [16]

In order to control car pollution with CO_2 gas, the EU sets CO_2 emission standards for new cars (g/km). The EU has set gradual year-on-year averages of CO_2 emissions, which apply to cars and vans made by any manufacturer (Fig. 9). Fuel consumption and CO_2 emissions 2013 was the first year in which average CO_2 gases emissions from new passenger cars fell below the 130 g/km target that applies from 2015 on.

As can be seen from Fig. 9, the concentration of CO_2 emissions from new passenger cars will not exceed 95 g/km by the end of 2020, which is 40% less than average emissions in 2007. CO_2 target for vans in 2020 is 147 g/km, which is 19% less than average emissions in 2012.

On the other hand, each country or region's "background" to CO_2 emissions from passenger cars depends on its level of economic development. Living standards determine the type/class of cars that residents use (operate), not to mention the age of the car fleet. This is illustrated by the diagrams in Figs. 10, 11 and 12.

If petrol and diesel cars have very similar values of CO_2 emission comparative indexes, the hybrid car's CO_2 "footprint" is about (30–40)% smaller (see Fig. 13).

In 2013, the number of new car registrations in the EU stabilized at around 12 million per year. It is noteworthy that since the peak of 2007 this number has been constantly decreasing, which in 2013 remained 20% below the said peak (Fig. 14). The largest EU Member States (Germany, France and the UK) account for up to 60% of all new car registrations [2]. As a result, in other EU countries, the car fleet is aging rapidly, while the toxicity of car ICE exhaust gases is steadily declining [17].

Passenger cars and trucks are currently subject to the EURO-6 emission standard (see Fig. 15). This regulation strictly defines allowed values of harmful substances

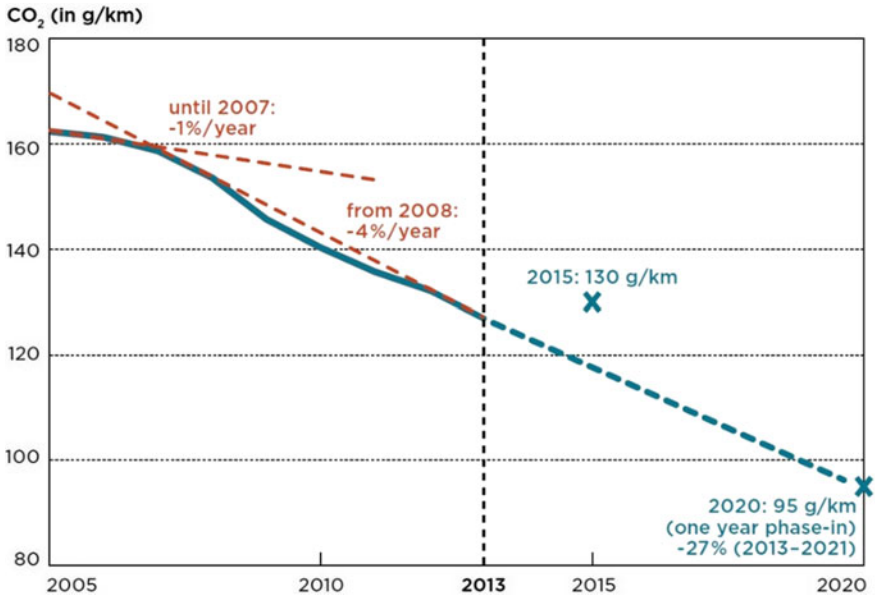

Fig. 9 Tendencies of CO_2 emission limits for new passenger cars in 2005–2015 [2]

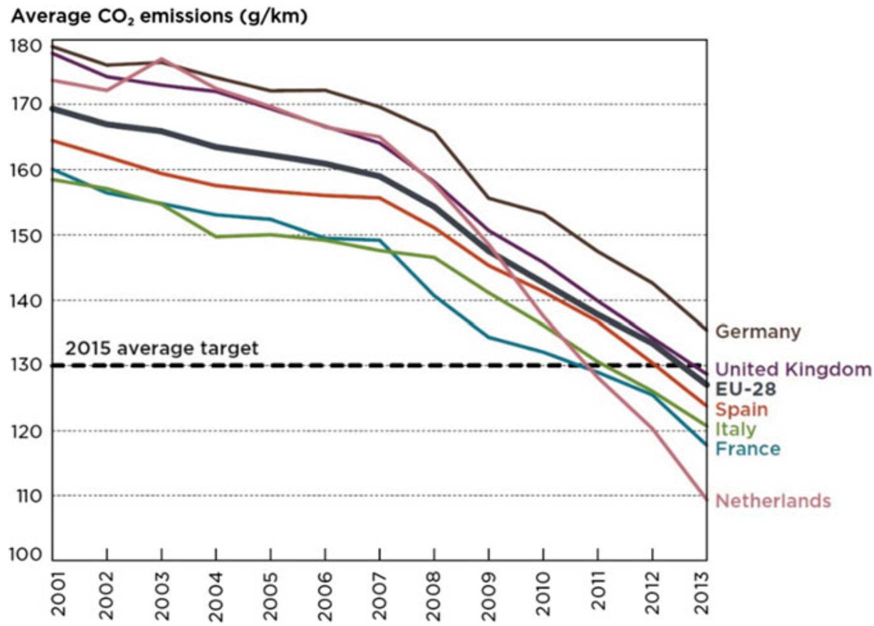

Fig. 10 The dynamics of the reduction of the comparative concentration of CO_2 in car emissions in different EU countries in 2001–2013 [2]

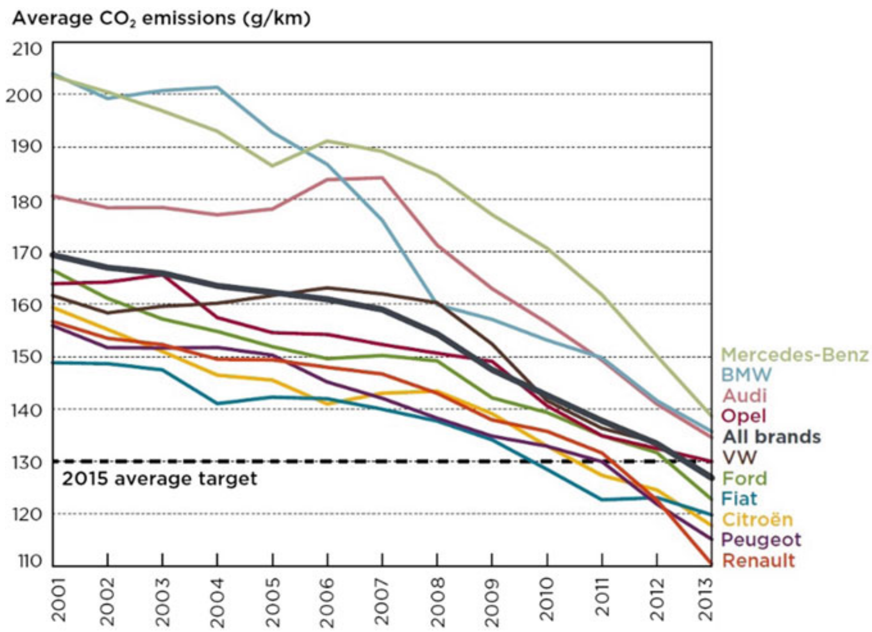

Fig. 11 Tendencies of CO_2 emission comparative indicators considering different car brands in 2001–2013 [2]

(carbon monoxide CO, non-methane hydrocarbons NMHC, hydrocarbons HC, particles, PM substances and nitrogen oxides NO_x) in the exhaust gases of ICE [12]. These radical reduced concentrations of toxic substances in ICE exhaust gases of the latter years are shown in the diagram of Fig. 15.

The EURO-6 standard sets limits for CO_2 concentrations which are 68% lower and even 96% lower for particulate matters than in 1992. By comparing EURO-4 with EURO-6, NO_x emissions from nitrogen oxides have been reduced by 68%.

On the other hand, with the reckless tightening of ecological standards, automotive engineers are starting to shuffle in order to maintain competitive vehicle ICE parameters in the market. This has even led to a worldwide scandal. In September 2015, Volkswagen AG shocked the automotive world when it admitted to allegations made by the USA Environmental Protection Agency (EPA) that it had manipulated its software to cheat on emission tests. The company admitted to installing specifically designed software, called defeat devices, to fool emission testers, allowing its cars to become certified even though, in actual use, they emitted 10–40 times the amount allowed by EPA guidelines.

It should be noted that no matter how strict the ecological standards for ICE exhaust gas are, as long as we do not limit the concentrations of harmful substances in ICE combustion, the main problem—CO_2 emissions—remains unsolved. The same goes for the incredible refinement of ICE engine designs for vehicles, especially cars, in recent decades. The fuel economy of the ICE, that is the comparative

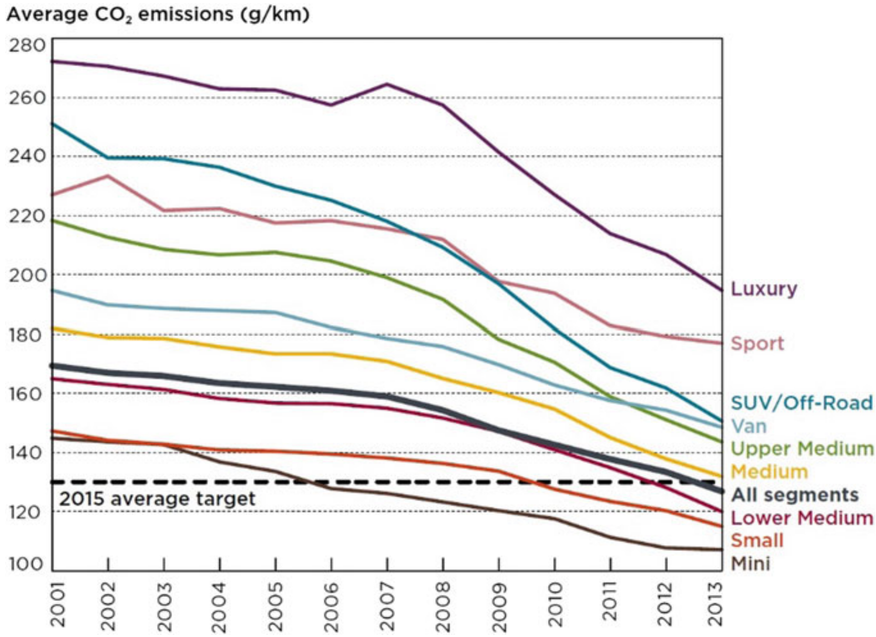

Fig. 12 Trends of car CO_2 emissions comparative indicators considering passenger car classes in 2001–2013 [2]

fuel costs, has fallen several times since the 1970s. Significantly improved fuelling systems and electronic control have at the same time significantly improved the combustion process in ICE combustion chambers. This resulted in a few times cleaner combustion and emissions. Considering the improving CO_2 comparative indicators and the implementation of the requirements of the EURO-4, EURO-5 and EURO-6 standards, an equally impressive reduction in CO_2 emissions could be expected. However, the total absolute CO_2 emissions have been "restored" by the global vehicle fleet, which has grown inversely in proportion to the reduction in exhaust gas toxicity. This is illustrated by the example of the EU fleet: the average CO_2 comparative indicator for the entire car fleet is reduced by about 1.3% annually and the fleet is growing by about 1.5% annually (see Figs. 1 and 12). Even more complicated situation is predicted in East Asia region (Figs. 1 and 2). So, for now, GHG emissions are not falling, but on the contrary, rising. Over the last 10 years, their annual growth has been 2.2%, while during the period (1970–2000) annual GHG emissions were much lower, at just 1.3%. In selecting recommendations for necessary actions, the researchers identified safe atmospheric concentrations of CO_2 (450 ppm) that must not be exceeded in order to prevent global warming above 2 °C compared to pre-industrial levels.

As mentioned earlier, the increasing stringency of requirements for CO_2 and other harmful exhaust gases makes it urgent to search for replacement fuels, or at least their additives. Hydrogen may be used as a partial additive and/or substitute for fossil fuels

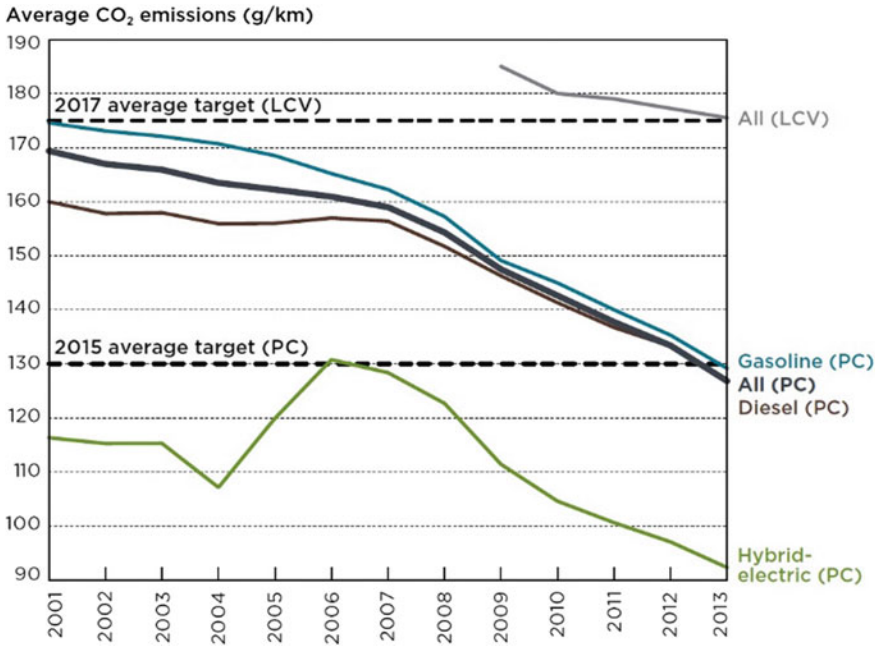

Fig. 13 CO_2 comparative emissions from cars depending on ICE and powertrain technology [2]

for a transitional period before a significant part of the vehicle fleet is electrically powered [19–22]. Hydrogen is an alternative fuel, which does not contain carbon [23].

The research, innovation and competitiveness dimension is based on low CO_2 and clean energy technologies. In order to significantly reduce emissions from the transport sector, there is an urgent need to "decarbonize" the ICE fuels during the transitional period "ICE-to-electric" without tactile changing the habits of the population (drivers) and without reconstruction of customary re-fuelling infrastructure (network of petrol stations). This will inevitably require further research into the different types of alternative fuels and their potential for use in conventional ICEs [24]. At present, vehicles using alternative fuels or their additives still have technical limitations such as limited mileage and high energy costs/losses. Research and innovation, transforming the EU into a low-carbon society will depend on the rate on which these new technologies are deployed in the transport sector, particularly for the road transport. In the transport sector, low-carbon technologies that are at least cost-competitive are not yet available.

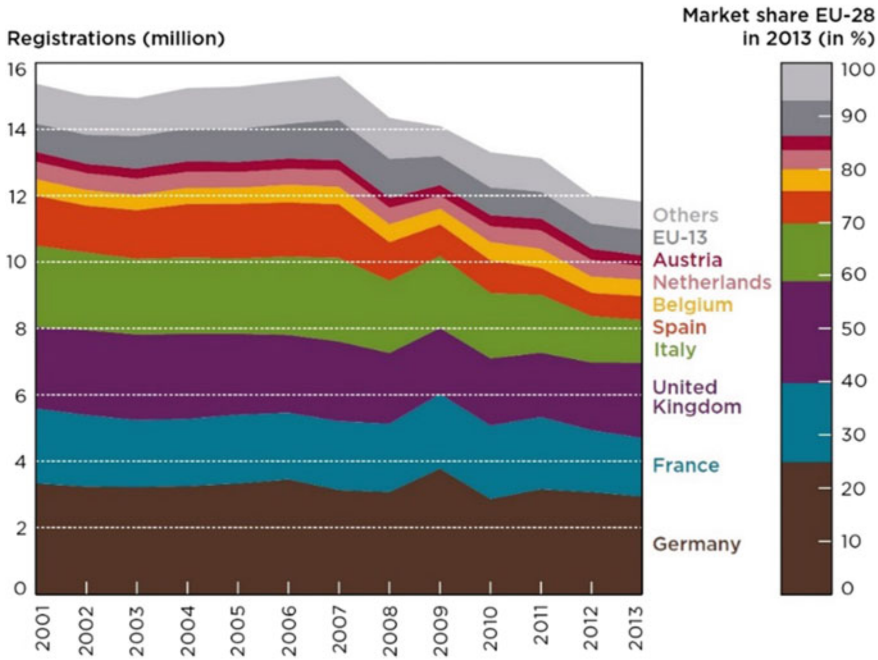

Fig. 14 Statistics of new passenger car registration by EU Member States [2]

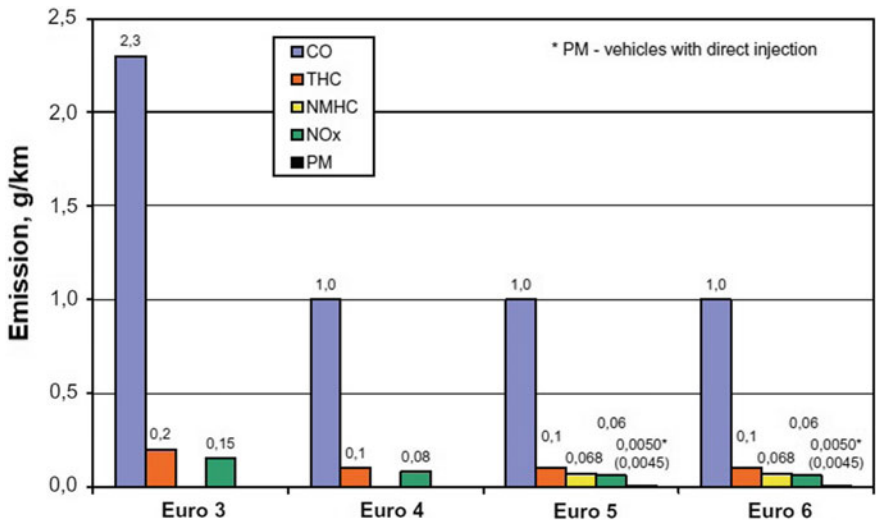

Fig. 15 Dynamics of requirements Euro emission standards [18]

3 Global Process of Shifting from Internal Combustion Engines to Electric Powertrains

With European Union member states continuously increasing the use of renewable resources to reduce environmental pollution and dependence on fossil fuels, also with increasing use of electric cars, it is crucial for decision-making states to have a fully-fledged and independent view on the development of use of electric transport and opportunities to promote the creation of proper infrastructure of electric cars.

According to the data of the global survey of randomly selected participants carried out in 2011, 68% of respondents would like to shift from conventional internal combustion engine cars to electric cars, while 60% of the surveyed persons would consider purchasing an electric car as their new vehicle. A Swedish market survey found that about 37% of respondents planned on buying an electric car within 10 years [25–27].

The results of a survey conducted in China [28] show that concerns about urban smog and air pollution, also an affordable price of electric cars are the main drivers for purchasing an electric car. Moreover, such factors as governmental subsidies, consumer age and marital status also have a major influence on consumer willingness to purchase an electric car.

Surveys show that today the price is the main obstacle to electric cars becoming a mass-market product, as it is much higher than the price of conventional cars. The price of lithium-ion batteries has been dropping by 6–8% every year, which should increase production volumes. The conducted studies show [25, 29, 30] that the purchase price accounts for the major share of costs of operation of electric cars, which outweighs all the advantages of using an electric car, such as fuel economy, cheaper operation and maintenance due to a fewer wearing parts. This will last until technological advantages and economies of scale reduce battery prices. In the long run, costs of operation of electric cars purchased in the European Union in 2020 are forecasted to become the same as the price of operation of internal-combustion engine cars over their 9 years of operation span, had the current governmental incentives not applied. If the incentives were also taken into consideration, the break-even point for electric cars would be achieved in a mere one year of operation [25, 31, 32].

The distance travelled by a single battery charge is another obstacle to an increasing use of electric cars. Today, electric cars can travel about 100–160 km on average until the next charge. The distance travelled by electric cars also greatly depends on the driving style (aggressive or high-speed driving drains batteries faster), interior climate, temperature settings of the car, and road conditions. The ability of an electric car to reach the planned destination may depend on these factors. This discourages drivers and still makes them choose conventional internal combustion engine vehicles, which can travel more than 800 km at full tank without refuelling. According to survey data, 74% of respondents from Europe believe that the minimum distance travelled by an electric car should be about 480 km, although 80% of drivers travel an average of 80 km per day. Most electric cars available on the market today can easily cover the average distance, but consumer expectations for passenger car mileage are based on the capacities of internal combustion engine vehicles [25, 33].

The convenience, price and time indicate that most electric cars will be charged at night at home or at work. This is a great solution when using an electric car for daily commuting, but it is not suitable for travelling longer distances or when drivers cannot charge their electric cars at home or at work. Therefore, the installation of a fast charging infrastructure is necessary to increase the demand for and interest in electric cars and to eliminate inconveniences of using them. This is how the number of users could be increased from a small group of enthusiasts and people looking for a second car to increasingly more users. However, having combined a high price and a low payback indicator with high risk of technology obsolescence, prospects for private sector service providers are rather poor due to ever-evolving technological solutions [25, 34].

In order to increase electric car sales, they could be exempted from VAT. While tax incentives do not have a significant influence on consumer decision to purchase an electric car, they should be taken into consideration at least till until some alternative subsidies are offered. New internal combustion engine vehicles should be subject to higher VAT rates. Such a system already works in Norway, the Netherlands and France [35, 36]. Higher tax levies collected could be directed towards the development of electric car infrastructure. This system could function much longer than discounts, grants, or the governmental tax programmes. Nonetheless, this system may be disadvantageous for political reasons, thus the provision of incentives for electric cars would be more advantageous. Such a system has been implemented in the United Kingdom. An early termination of incentives for electric cars can have a negative impact on their market development. Offering incentives till electric cars have a strong presence in the automotive market would be best [36, 37].

After electric cars become well established in the market, poorly managed electric car infrastructure can cause a heavy load on electricity distribution networks, which can in turn lead to serious system reliability and stability problems. To avoid these problems, developing an effective scheme to control the charging of electric cars using advanced information and communication technologies is necessary [38–40]. Electricity suppliers should promote battery charging when it is most useful for the network. Charging should be encouraged during periods of under-capacity or during peak hours of generation of electricity from renewable energy sources rather than during peak load periods of the system. Differing charging rates and application of rational tariffs are the two ways to control the charging flow of electric cars choosing optimal time slots [41, 42]. Future developments in charging infrastructure may also affect the charging habits of electric cars. In cases when night-time charging is more beneficial, investments should not be made in public charging stations which users visit during the day or evening, for example, shopping malls, cinemas and wellness complexes, investing in residential neighbourhoods instead [42].

Many countries around the world have been developing plans for electrification of their transportation systems to reduce greenhouse gas emissions and improve air quality in cities. The basis for such plans is the integration of electric cars, but this solution faces the problem that most consumers fear short electric car traveling distance compared to conventional cars. This problem can be resolved by installing more charging stations, but this is problematic as it is necessary to find out how many of them are actually needed and what would be the best place for their installation. The solution to these problems depends on many factors, such as the maximum distance that electric cars can travel, charging stations, and the cost of their installation [43].

A poorly managed electric car charging infrastructure can cause heavy load on electricity distribution networks, which can lead to serious system reliability and stability problems. To avoid these problems, developing an effective scheme to control the charging of electric cars using advanced information and communication technologies is necessary [40].

The load created at the time of charging electric cars will have the greatest impact on the quality of the electricity supplied in low voltage networks compared to high voltage networks. Voltage drops are higher when a low voltage network is farther from the electricity substation. Charging an electric car when a charging station is at the maximum permissible distance from the electric transformer station causes a much higher load than if the station was close to the transformer station. The observed voltage drop at the electric charging station load of 240 V/30A is approximately double than at the 240 V/16A charging stations. Having connecting several electric cars to the same charging station, voltage will drop even further in the measured low voltage network. A voltage drop in a low-voltage network after connecting an electric car to a three-phase transformer is similar to that of a one-phase transformer [39].

Charging electric cars creates the highest load on electricity networks when all electric cars to be charged have fully discharged batteries and they are being charged in full. The lowest load is created when batteries being charged have different battery discharge levels. In order to reduce the difference between loads and to resolve problems relating to forecasting and preparation of loads, the use of comprehensive flow information on different loads at different charging stations and time should be developed. The developed model of place and time of electric car charging loads on electricity networks could help electricity and charging service providers plan distribution systems in future electricity networks. Moreover, this model can also help in deciding on investment and operational plans for adaptive electric car charging infrastructure using renewable energy resources and energy saving systems depending on the need for electric car charging power [38].

According to the "European Strategy for Clean and Energy Efficient Vehicles" [44], all electric cars should be subject to the same standards, creating opportunities for all electric cars to be charged and to connect to electricity networks throughout the EU with all types of chargers [45].

According to Eurostat data, the number of registered electric cars has been continuously increasing (Fig. 16). It quadrupled in four years from 2013 till 2017. Such a growing trend has been observed in all electric vehicles (starting with fully electric cars and ending with hybrids).

Such shifting trends lead to a very rapid development of this segment of economy, taking into account the current research development trends, which encourage not

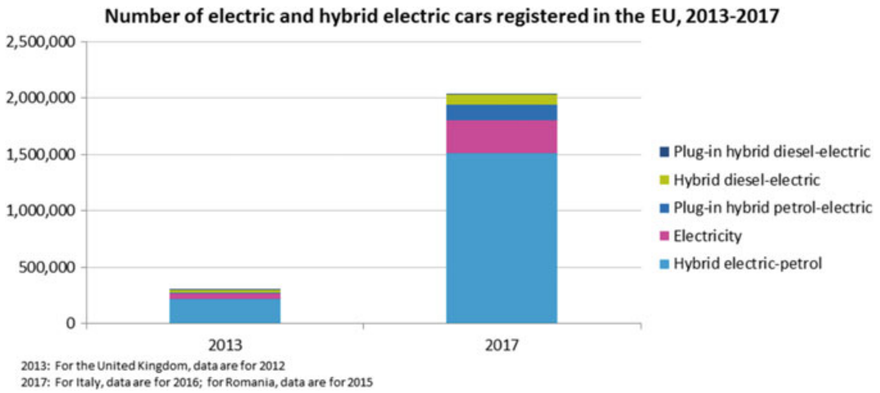

Fig. 16 Number of electric cars registered in the EU in 2013–2017 [46]

only the development of more advanced charging systems, but also the design, testing, certification and manufacture of cars themselves.

4 Potential of Producing Carbonless Alternative Fuel for Internal Combustion Engines of Vehicles

European Union Member States are committed to implementing the new Directive 2009/28/EC of the European Parliament and of the Commission (Directive 2003/30/EC of the European Parliament and of the Council was repealed in 2009), which promotes the use of energy from renewable sources. The plan is to use this method to replace 10% of mineral fuels used in transport with biofuel by 2020 and to use plant biomass in EU Member States in order to contribute to such goals as meeting the requirements for mitigating climate change and ensuring safe and environmentally friendly use of energy [47].

Currently, the environmental quality of vehicles with internal combustion engines is assessed in application of standard requirements for a driving cycle [48, 49]. There also are special standards for vehicles with internal combustion engines (EURO-3, EURO-4, EURO-5 and EURO-6) aimed at reducing nitrogen oxides, carbon monoxide, hydrocarbons and particulate matter in exhaust gases. These requirements have become increasingly more stringent. Having compared the requirements for petrol-powered vehicles laid down in EURO-2 and EURO-6, the nitrogen oxide emissions norm was reduced by more than 60% (from 150 to 60 mg/km), and the norm for hydrocarbon emissions—by more than 64% (from 200 to 330 mg/km) [49].

Biofuel, which has both environmental (lower particulate matter emissions during combustion) and social benefits (using local biomass and bio-waste resources, creating the opportunities to create new jobs in the production region), has been used

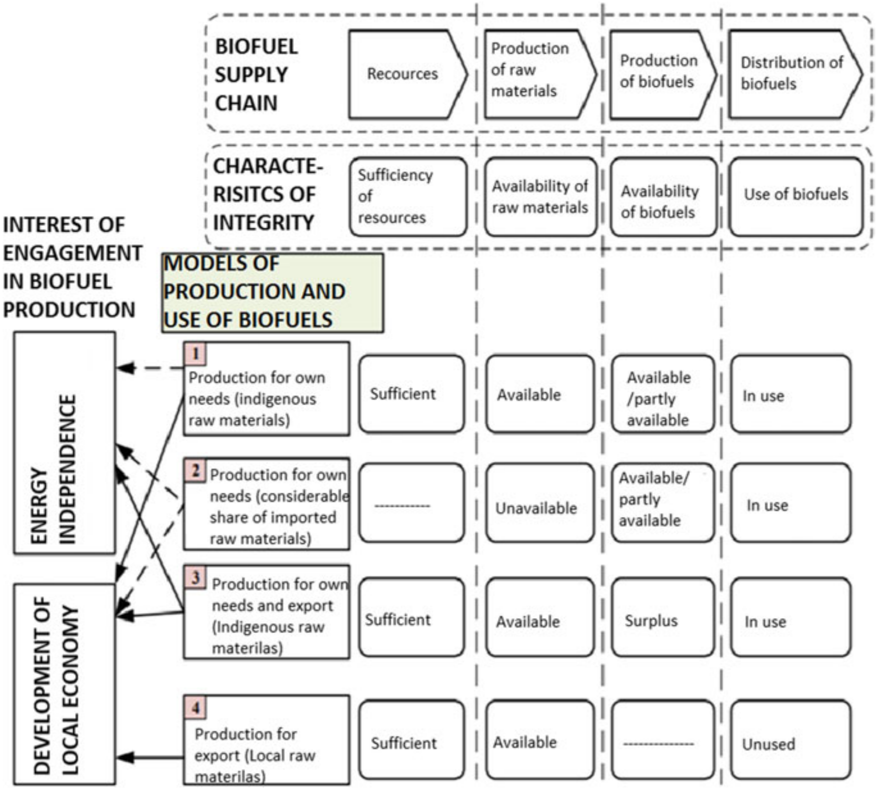

Fig. 17 Models of production and use of biofuel [50]

to ensure these requirements. Various strategies, which identify the factors affecting the use of biofuel, have been developed to this end (Fig. 17).

The key distinguished integrity characteristics show the characteristics of biofuel production and use that directly affect the geography of use of biofuel. Any use of biofuels leads to an uninterruptable biofuel supply chain, each element of which can be decisive from economic, social and political aspects of consumption. Therefore, two key areas of involvement in biofuel production are emphasized: energy independence and the development of local economy. All aspects of biofuel production and use in a specific region can be modelled and justified in light of these two areas.

Biofuel has a lower carbon content compared to conventional petroleum-based fuel. It can be derived from various resources (from direct use of biomass to waste recycling (Fig. 18).

The scheme illustrates (Fig. 18) that the main resources for obtaining the raw material can be classified as gaseous, which contain sugar, and gaseous containing fat. Different methods of biofuel production are used depending on the raw material, producing different biofuels. Several generations of biofuels can be distinguished. First-generation biofuel is fuel from food crops. Second-generation biofuel

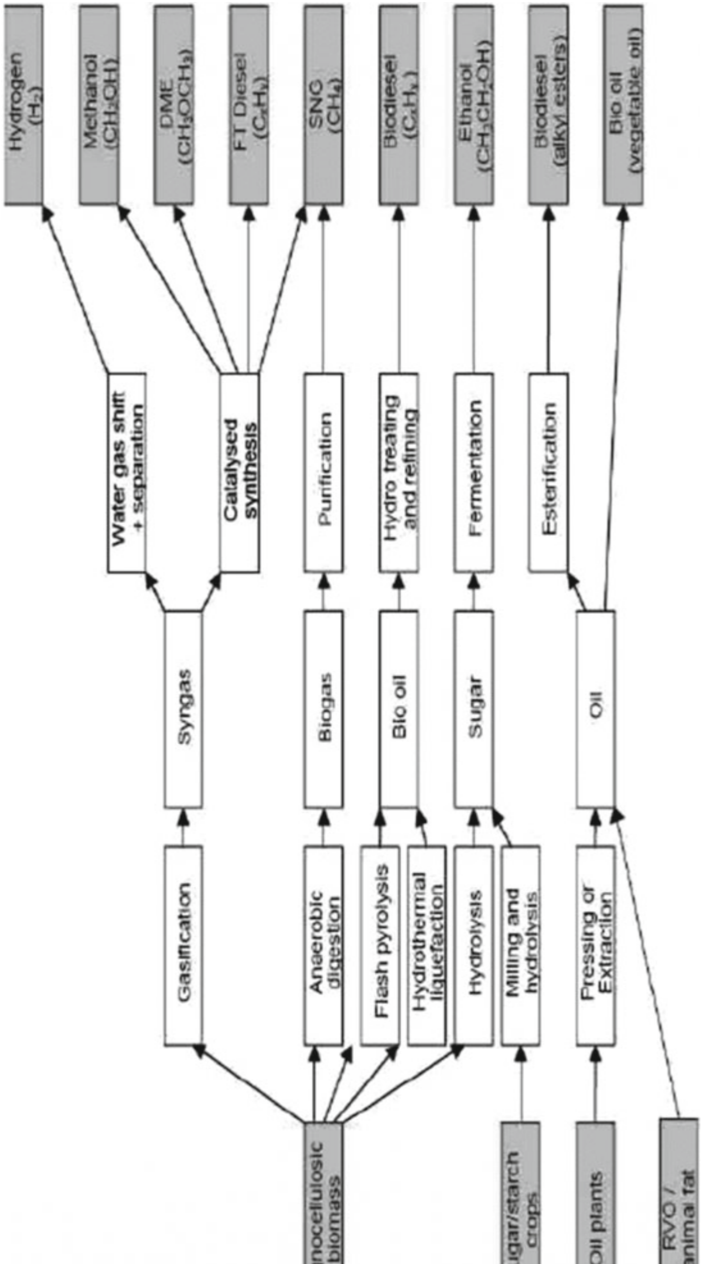

Fig. 18 Biofuel production scheme [51]

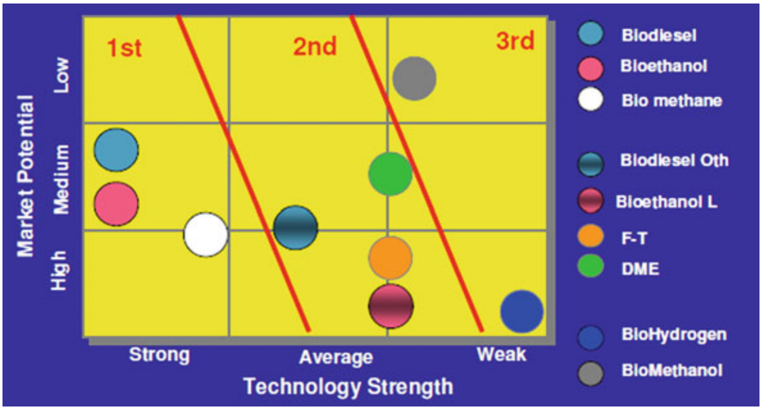

Fig. 19 Comparison of biofuel generation production technology development and the market [52]

is fuel using lignocellulosic biomass as raw material. In third-generation biofuel, the method of improving raw material has been selected instead of refining the fuel production process (as is the case of second-generation fuel). Various lignocellulosic plants are used in the process. Technologies of production of the fourth-generation biofuel involve the cultivation of genetically modified plants, which absorb significant amounts of CO_2 from the atmosphere in their stems, branches and leaves. Later, biofuels are effectively produced in biochemical processes using genomically synthesized microbe.

The scheme of Fig. 18 allows stating that there are technologies, which allow producing biofuel from any type and resource of biomass. The use of each generation of biofuel has its own advantages and disadvantages, which can be divided into market potential and the level of development of production technologies (Fig. 19).

Figure 19 illustrates that biofuel generations affect the strength of production technologies. It is understandable that first generation biofuels will have the highest level of development, because those technologies have been around the longest in comparison to others. Yet on the other hand, the higher the degree of biofuel generation, the greater the market potential opens up.

As per Fig. 19, the fourth-generation biohydrogen fuels are carbonless and have a significant market potential, even though the level of development of production technologies is still weak. Therefore, let's take a closer look at their production technologies.

4.1 Direct Biophotolisation Process

This is a photosynthetic production process of hydrogen and oxygen using water and sunlight. Microorganisms that make up the green sea vegetation are used. They are required to induce reversible and irreversible hydrogenation in hydrogen containing enzymes anaerobically in the dark. They direct the production of two protons (2nd+) to hydrogen and gaseous (H_2) in separate reactions, since the hydrogenogenesis process breaks down water into separate gases (hydrogen and oxygen), thus these gases must be separated. One of the applicable methods is the supply of CO_2 gas to hydrogen-enriched enzymes, at the time of which photosynthesis takes place, and this is when marine vegetation uses anaerobite synthesis with light to produce gaseous hydrogen [52–55].

4.2 Indirect Biophotolisation Process

It uses cyanobacteria and blue-green marine vegetation, where CO_2 emitted in photosynthetic process is supplied as a substrate for hydrogen-rich enzymes at the molecular level. The process is necessary to ensure normal photosynthesis at the beginning of cultivation of bio-flora. Cyanobacteria contain several enzymes directly involved in hydrogen gas metabolism. Nitrogenase, which catalyses nitrogen needed to produce hydrogen, is most important here. The other enzyme oxidizes and then synthesizes hydrogen during hydrogenesis. Hydrogen production rates depend on the type of cyanobacteria and process conditions [56].

4.3 Photofermentation

This process uses purple sulfur bacteria to produce nitrogen-catalysed hydrogen using light and smaller compounds such as organic acids. In this process, hydrogenation competes for hydrogen in nitrogenation. One of the parameters, which has the greatest impact on photo-fermentation, is the intensity of light, leading to increased efficiency and speed of hydrogen production. Hydrogen production rates have been found to be faster when cells are immobilized when bound in the liquid phase [57, 58].

4.4 Gas Exchange Reaction (Hydrogen Gas Changes Reaction)

Certain photoheterotrophic bacteria in Rhodospirillaceae family can grow in the dark using CO as the only source of carbon to create ATP, with H_2 and CO_2.

In these microorganisms, hydrogen is produced in enzymatic reactions at certain temperatures and low pressures. The enzyme responsible for capturing CO oxidizes in oxidation-reduction reactions in CO hydrogenation (CODH) process and remains a membrane-bound enzyme complex. This process can be very promising for CO gas utilization and hydrogen production [59–62].

5 Advanced Technologies of Hydrogen Using in Internal Combustion Engines

5.1 Review of Hydrogen Fuel Properties

Hydrogen is one of the most promising energy accumulators, which can meet energy-related needs, ensure environment protection and its sound development. Fossil and biological sources of energy may be used in H_2 production, separating in them CO_2 and storing carbon compounds in geological structures. Hydrogen can be found in chemical compounds, such as natural gas, coal, biomass and water, but pure hydrogen does not exist on Earth [63, 64].

Hydrogen is extracted in many ways. Hydrocarbon distillation (reforming process) is currently the most common method of hydrogen extraction [65, 66]. This process may use any hydrocarbon, but the use of natural gas allows achieving efficiency coefficient of up to 80%. Carbon dioxide also forms during this highly energy-intensive process. In order to reduce emission effects to the maximum, centrally produced carbon dioxide (CO_2) can be captured and stored or mineralized. Since hydrogen is a carbonless fuel, its combustion does not produce CO_2 or smoke [51, 67–69].

Pure hydrogen is produced from water by way of electrolysis, using electricity generated by burning fossil fuel [70] or using water, wind and solar energy [71, 72]. Biomass conversion, the method most commonly used to produce hydrogen, is also considered to be a renewable energy source [73, 74].

The ignition range of the hydrogen/air mixture is very wide compared to other fuels (Table 1). Based on this property, hydrogen can be said to be able to burn in internal combustion engines at different fuel-air mixture ratios. The main advantage is that the use of lean mixtures results in significant savings and a more complete combustion reaction. The final combustion temperature is also lower, which reduces the amount of emitted nitrogen oxides. Hydrogen ignition requires about six times less energy than petrol. This feature allows igniting very lean hydrogen-air mixtures in internal combustion engines and ensures a fast combustion. Unfortunately, low energy required for ignition causes problems related to spontaneous ignition [75–77].

5.2 Use of Hydrogen in Internal Combustion Engines

In order to use more effective alternative fuel sources, hydrogen is one of the most promising elements and energy accumulators. Hydrogen reduces greenhouse gas emissions and increases the efficiency of internal combustion engines. The following types of hydrogen may be used in the engine:

(1) pure hydrogen;
(2) hydrogen and natural gas (biogas, synthetic gas) mixtures;
(3) petrol and hydrogen (dual fuel spark ignition engine);

Table 1 Fuel properties [78–81]

Indicator	Dimension	Hydrogen	Petrol	Diesel
Chemical formula	–	H_2	C_8H_{18}	$C_{12}H_{23}$
Composition of main elements by mass	%	100 H	85–88 C, 12–15 H	84–87 C, 13–16 H
Molecular weight	g/mol	2	100–105	200–300
Lower heating value	MJ/kg	~120	~44.5	~42.5
Density at $t = 0$ °C and $p = 0.1$ MPa	ρ, kg/m^3	~0.09	~750	~850
Boiling temperature	°C	−253	25–215	180–360
Freezing temperature	°C	−260	−40	−34
Specific vaporization heat	kJ/kg	~120	380–500	~250
Auto ignition temperature	°C	560–585	260–460	180–320
Minimum ignition energy	mJ	0.017	0.29	–
Flame velocity	m/s	2.65–3.25	0.30–0.50	0.22–0.25
Flame temperature	°C	2207	2307	2327
Cetane number	–	5–10	8–14	45–55
Octane number	–	130	95–98	30
Stoichiometric A/F ratio on mass basis	kg/kg	34.5	14.7	14.6
Flammability bounds of the combustible mixture by stoichiometric A/F ratio λ	–	0.14–9.85	0.3–1.5	0.82–12
Flammability limits vol. in air	%	4–77	0.6–8	0.6–7.5
Diffusion coefficient	cm^2/s	0.63	0.08	–

(4) diesel and hydrogen (dual fuel in compression ignition engine);
(5) when using dual fuel, petrol or diesel may be partially or completely replaced by liquid biofuel, hydrogen may be blended with various gases [82].

5.2.1 Use of Pure Hydrogen in SI ICE

Hydrogen or its mixture with other gases can also adversely affect engine performance. Physicochemical properties of hydrogen may reduce engine power and torque [83]. When supplying hydrogen gas to the intake manifold, it takes up volume and

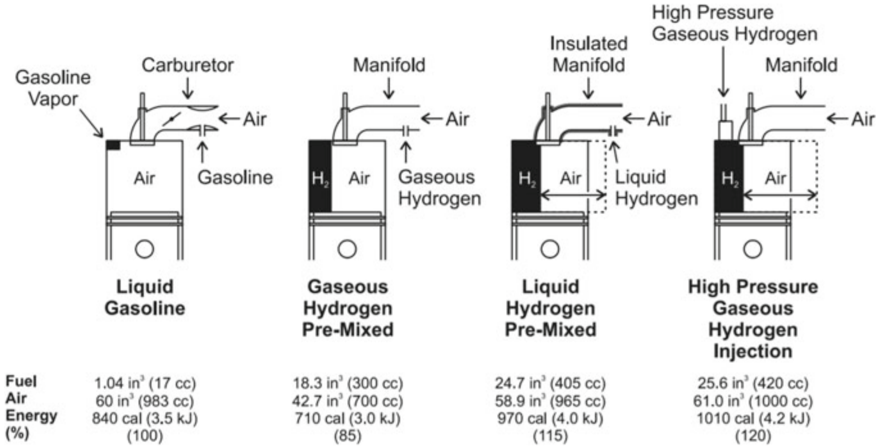

Fig. 20 Engine volumetric efficiency and created energy comparison using various petrol and hydrogen supply systems [68]

reduces volumetric efficiency of the cylinder. As a result, the amount of fuel supplied to the cylinder and energy released during the cycle decreases (Fig. 20). The use of direct injection allows avoiding the power reduction problem, eliminating the possibility of intake mixture igniting in the manifold. However, the temperature of spontaneous ignition of hydrogen in the cylinder cannot be easily forecasted. Unlike other high-octane fuels (such as methane), octane number of hydrogen changes non-logarithmically, and this causes problems with mixture ignition control [84].

At low engine loads, engine power may be regulated by increasing excess air in the mixture, while combustion temperatures are below the NO_x formation temperature. Then the engine runs at full throttle, and upon the reduction of injection losses, the effective efficiency coefficient increases [85]. However, at high engine loads, a tendency of a hydrogen and air mixture to ignite too early leads to technical problems [86]. The use of small amounts of hydrogen and combustible mixtures allows achieving higher *BTE*. A hydrogen additive supplements the lean gasoline-air mixture and improves its combustion.

A single cylinder SI engine was tested by injecting hydrogen into the intake manifold. Tests have shown that when operating on hydrogen, the maximum engine power was ~20% lower than when using petrol. When using hydrogen, efficiency coefficient of the engine was ~2% higher than that of gasoline. CO, CO_2 and HC concentrations in exhaust gases were negligible when using hydrogen, but at maximum engine load, NO_x concentration was four times higher than that of petrol. Using hydrogen, which has a higher burning rate, ignition advance angle had to be reduced compared to that of petrol. Hydrogen injection pressure was determined to have no significant impact on engine indicators [87].

5.2.2 Use of Natural Gas and Hydrogen Mixtures in ICE

The use of hydrogen and natural gas fuel mixtures can reduce CO, CO_2 and HC emissions, however, emissions of nitrogen oxides increase due to increased combustion temperature [88, 89]. It was determined that in order to achieve maximum engine efficiency when using hydrogen as an additive in fuel mixtures, correctly determining the spark ignition moment was necessary [90].

The changing of composition of natural gas and hydrogen revealed that the maximum BTE of the engine can be achieved with a 30% H_2 additive in stoichiometric combustible mixture ($\lambda = 1$). Under lean combustion conditions ($\lambda = 1.4$), the maximum *BTE* is achieved with a 70% H_2 additive in natural gas. Increasing H_2 concentration in the fuel mixture decreases the *BSFC,* and the lowest index values are obtained with 90% H_2 under both stoichiometric and lean combustion conditions. In order to reach the best engine performance indicators, the ignition moment must be delayed and adjusted to appropriate H_2 concentration in natural gas. The engine torque decreases when using mixtures of natural gas and hydrogen containing up to 20% H_2, but when increasing H_2 concentration, the torque increases consistently and the maximum value is reached when H_2 is 70%. Increased combustion temperature intensifies NO_x formation in the engine cylinder, but when using H_2 in fuel mixtures up to 30%, the measured NO_x emissions under both stoichiometric and lean combustion conditions do not exceed the emission levels for gasoline [19].

Direct injection into engine cylinder is one of the methods to increase engine efficiency, to achieve a better formation of a flammable blend in the cylinder, a higher torque and to reduce intake losses [91]. Combustion process in the cylinder significantly depends on the following parameters: injector nozzle, injection pressure, injection time and duration, the engine head and geometric form of the piston [92–94]. With direct fuel injection, soot formation problem is faced [19, 95]. This problem is also relevant with gas fuel, when layered combustion is used—fuel is injected at the end of the compression stroke.

5.2.3 Use of Petrol and Hydrogen (Dual Fuel) in SI ICE

Hydrogen quenching distance to an obstacle is approximately three times lower than that of gasoline, so the flame of the hydrogen—petrol mixture spreads closer to cylinder walls, effectively burning mixture in the volume. The introduction of hydrogen in the mixture alone leads to a decline in the total carbon content in the fuel mixture, resulting in lower CO_2 and CO emissions. Nitrogen oxide emissions depend on the oxidation temperature in the cylinder, and the nitrogen oxide content increases proportionally when increasing hydrogen content in the flammable mixture [96]. Numerical simulation of the combustion process of petrol and hydrogen mixtures and experimental tests showed that having increased H_2 concentration to 3%, the maximum flame front velocity increases from 11.1 to 15.2 m/s (~37%), and after increasing the H_2 concentration to 6%, the flame velocity increases to 17.8 m/s (~60%) [97].

5.2.4 Use of Diesel and Hydrogen (Dual Fuel) in CI ICE

Diesel engines are widely used, in the transport and energy generation sectors in particular, due to their higher efficiency coefficient. However, it is well known that NO_x and particulate matter emissions are important problems in the use of diesel engines. Therefore, many researchers are looking to increase the efficiency of diesel engines and reduce their emissions. In many studies, hydrogen has been used to reduce the extent of the use of fossil fuels [98].

The use of hydrogen as an alternative fuel in diesel engines has started recently. Hydrogen ignites spontaneously at the temperature of 858 K, which makes the use of pure hydrogen under pressure only hardly possible. A spark or another auxiliary source of energy could be a source of ignition of hydrogen [99]. The use of glow plugs or ceramic combustion chamber components, which would ensure good heat retention in the combustion chamber, would make ignition of a hydrogen and air mixture possible [100].

Thus, dual-fuel system, where the ignition source is diesel, and hydrogen gets into the combustion chamber with air, has normally been used in research with hydrogen-powered diesel engines. This principle of use of hydrogen indicates that the higher the amount of hydrogen supplied to the engine, the more the smoke level of diesel engines decreases, but the nitrogen oxide content increases in proportion to hydrogen content, as does the combustion process noise, which is affected by a high hydrogen combustion rate [68, 101].

The use of hydrogen in a diesel internal combustion engine is expedient. First, hydrogen improves the H/C ratio in the overall flammable mixture. Second, by injecting small amounts of hydrogen into a diesel engine, good dispersing and mixing properties of hydrogen can reduce the heterogeneity of the diesel jet. As a result, the combustible mixture mixes better with air and becomes more homogeneous. A high hydrogen combustion rate reduces the combustion time of the mixture. The speed of the spread of hydrogen flames under normal conditions is 2.65 to 3.25 m/s and is almost 5 times higher compared to conventional hydrocarbon fuels. Better homogeneity of the combustible mixture provides better conditions for complete combustion. Fast combustion also contributes to an increase in the effective efficiency coefficient, as combustion occurs with lower heat losses to the combustion chamber walls. Moreover, hydrogen has a short flame-retardant distance, thus hydrogen flame spreads closer to the cylinder walls [101].

At low loads, hydrogen can cause problems with ignition. Dual-fuel operation suffers from relatively poor combustion efficiency at low-load conditions due to high unburned hydrogen rates. High rates of EGR and hence increasing the in-cylinder combustion temperature was found to be the optimal approach for improving the combustion efficiency and reducing NO_x emission. An early diesel main injection could also contribute to combustion efficiency improvement, but considerable injection advancements would increase the NO_x formation [67].

The analysis of the use of pure hydrogen in an engine operating in HCCI mode revealed instability of combustion due to uncontrolled start of combustion. Hot areas of the combustion chamber and the piston surface were assumed to likely be the cause of uncontrolled ignition of hydrogen. Moreover, ignition would start early, and would not develop the torque, which was achieved with diesel engine. In order to improve engine performance, the cooling of EGR and/or air and hydrogen mixture should be used [102].

Test results have shown that having enriched air with 30% of hydrogen, the effective efficiency coefficient, without detonation over the full load range, increases from 22.8 to 27.9%. They also revealed that with increasing percentage of hydrogen, the comparative fuel consumption, smoke, particulate matter content and HC concentrations in the exhaust were declining throughout the entire operating range. Supply of more than 30% hydrogen content reduces NO_x concentration in combustion in exhaust gases [103].

Air-fuel ratio, engine rotation speed and break torque have an impact in the performance and emission of diesel engines with hydrogen enrichment. *BTE*, *BMEP* and *BSFC* dependent on the operating conditions of the engine. The reduction in unburned hydrocarbon, carbon monoxide, carbon dioxide, particulate matter and smoke are observed when adding the hydrogen. However, nitrogen oxide is increased when enriching H_2, but this increase in NO_x can be controlled by multiple injections, exhaust gas recirculation or water injection as well as exhaust after-treatment [104, 105].

One more type of dual-fuel engine is high-pressure direct injection (HPDI) engine with an integrated gas/diesel injector (Fig. 21). Diesel is injected before injecting gaseous fuel and acts as a pilot gas ignition source. The HPDI dual-fuel engine has lower THC emissions and can replace most of the diesel with gas, but is not able to operate in pure diesel mode. But the HPDI system is more expensive than the dual-fuel system with gas injection into intake manifold, because this requires a completely new combined gas/diesel fuel supply system, including an engine controller, high-pressure fuel pumps (gas and diesel), and special dual injectors [106].

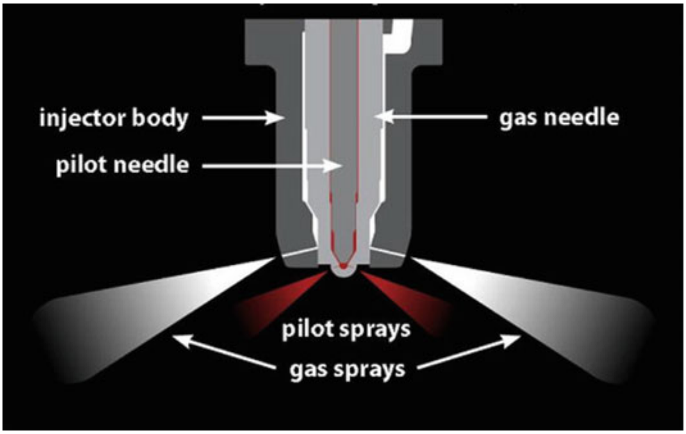

Fig. 21 Injector of high-pressure direct injection [106]

High hydrogen additive amounts allow reducing emissions of particulate matter, which requires the use of conventional diesel engines for lean mixtures. The HPDI dual-fuel engine can operate at a stoichiometric air-fuel ratio to ensure the maximum thermal value of the mixture and *BMEP*. Hydrogen injection in the high-pressure phase of the engine cycle further increases *BMEP*. The main problem with hydrogen combustion is a high auto-ignition temperature. Other challenges include the maximum pressure increase and hydrogen spontaneous ignition pressure. This affects the formation of NO_x emissions which may be resolved by EGR [107].

5.3 Brown's Gas Production Technology

Accumulating and storing hydrogen is difficult; it requires expensive equipment which can maintain high gas pressure (70 MPa) [108]. A water electrolyser allows producing hydrogen in a car itself and immediately using it [109]. Water electrolysis generators are of two types:

1. Decomposing water into hydrogen H_2 and oxygen O_2 gas separately. Oxygen is released in the electrolytic cell at the anode and hydrogen—at the cathode. Gases emitted at the positive and negative electrode are collected separately.
2. Producing Brown's gas—a flammable hydrogen and oxygen gas mixture [110, 111]. Many researchers call and mark this gas as HHO gas [112–116].

With potassium hydroxide (KOH) electrolyte solution, the voltage between electrodes can reach 2.0–2.5 V at a current density of 2000 A/m^2 and an electrolyte temperature of 80 °C [117]. Hydrogen and oxygen gases are separated between electrodes having installed an ion-conductive membrane, which prevents gas from mixing, but transmits OH^- ions.

In the absence of a membrane mounted between the anode and the cathode, hydrogen oxygen ions mix and produce HHO gas. In HHO gas, the volume ratio of hydrogen to oxygen gas is 2:1 (Fig. 22). Using 29.9 MJ of electricity, 1 kg of water produces ≈1240 l of hydrogen and ≈620 l of oxygen gas mixture with a total volume of ≈1860 l. At the pressure of $p = 0.1$ MPa and temperature $T = 0$ °C, oxygen gas density is 1.43 kg/m^3, hydrogen density is 0.09 kg/m^3 and HHO gas density is 0.54 kg/m^3. One litre of HHO gas contains 0.67 l of H_2 gas weighing 0.06 g and O_2 gas weighing 0.48 g. This gas mixture is explosive and highly flammable [118].

Car electricity network voltage is ≈14 V and this voltage is sufficient to power the section consisting of seven sequentially arranged electrolytic cells, each with a ≈2 V voltage (Fig. 22). Supply voltage is connected to the edge section plate, with six neutral electrode plates between them. All electrode plates are 0.8 mm-thick and made of 316 L stainless steel. The active area of one plate is 0.0144 m^2, and the total active area of plates of the section is 0.1 m^2. The plates are separated by 1.5 mm-thick gaskets made of alkali and acid resistant rubber. During the tests, KOH concentration in the electrolyte was 4%.

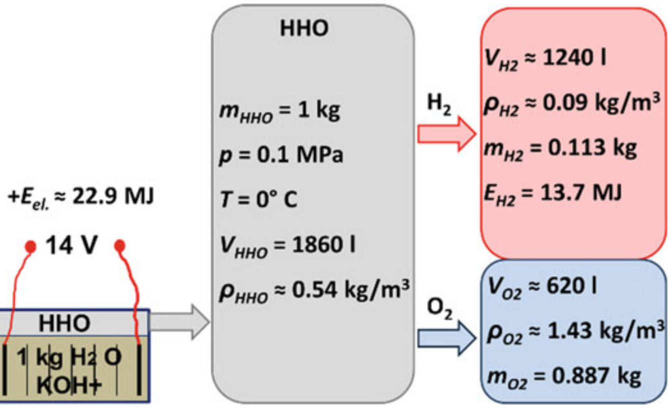

Fig. 22 Hydrogen energy concentration in fuel mixture

6 Prospective of Brown's Gas Additives as Substitutes of Fossil Fuels

6.1 Methodology for Analysing Indicators of Spark Ignition Engines

The efficiency of the use of Brown's gas is spark ignition (SI) engine was analysed by producing HHO gas additive using a mobile gas generator, which may operate autonomously (a research case) or this gas generator may be mounted in an operated car. An experimental study was conducted using Nissan Qashqai HR 16DE SI engine controlled by a programmable controller MoTeC M800. The key parameters of the engine are listed in Table 2. Tests were performed using laboratory test equipment, the scheme of which is presented in Fig. 23.

Table 2 Main parameters of engine "Nissan HR 16DE"

Parameter, dimension	Value
Number of cylinders	4
Cylinder bore, mm	78
Piston stroke, mm	83.6
Displacement, cm^3	1598
Maximum power, kW (rpm)	84 (6000)
Maximum torque, Nm (rpm)	156 (4400)
Compression ratio, ε	10.7
Fuel system	Multi point fuel injection
Valve mechanism	DOHC (dual overhead camshafts)

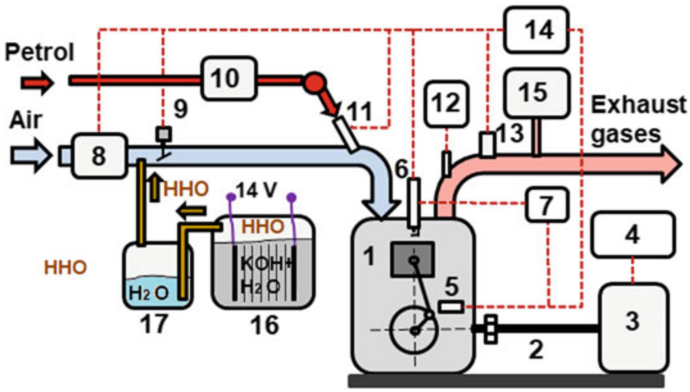

Fig. 23 The schematic of the engine testing equipment: 1—engine Nissan HR 16DE; 2—connecting shaft; 3—engine load stand AMX 200/100; 4—load stand electronic control unit; 5—crankshaft position sensor; 6—spark plug with integrated pressure sensor AVL ZI31; 7—equipment for registration of pressure in the cylinder AVL DiTEST DPM 800; 8—intake air mass flow meter Bosch HFM 5; 9—throttle control servo-motor; 10—petrol consumption metering device AMX 212F; 11—petrol injector; 12—K-type thermocouple exhaust gas temperature meter; 13—wideband oxygen sensor Bosch LSU 4.9; 14—engine electronic control unit MoTeC M800; 15—exhaust gas analyser AVL DiSmoke 40008; 16—HHO gas generator; 17—flame arrestor

Engine load stand *AUTOMEX AMX200/200* was used to measure the engine's brake torque M_B. The measurement accuracy was ±0.9 Nm. The hourly petrol consumption B_f was measured using an electronic fuel consumption meter *AMX 212F* with accuracy of ±0.10%. The accuracy of an intake air mass flow meter *BOSCH HFM 5* was 2%. Pressure in the cylinder p was measured using *AVL DiTEST DPM 800* device and a piezo sensor mounted on the spark plug *AVL ZI31-Y7S*. The sensitivity of the pressure sensor was 12 pC/bar and its accuracy—±0.01 MPa. The accuracy of a K-type thermocouple exhaust gas temperature meter was ±0.0075 × T. An exhaust gas analyser "AVL DiCom 4000" was used to measure the composition of exhaust gas, and the key device parameters are presented in Table 3. Emissions of individual components (CO, CO_2, HC and NO_x) were calculated in g/kWh units according to the approved methodology [119].

Table 3 Parameters of exhaust gas analyser "AVL DiCOM 4000"

Parameter	Dimension	Measuring range	Accuracy
CO	% (vol.)	0–10	±0.01
CO	% (vol.)	0–20	±0.1
HC	ppm (vol.)	0–20000	±1
NO_x	ppm (vol.)	0–4000	±1
O_2	% (vol.)	0–25	±0.01
λ	–	0–9.999	±0.001

HHO gas is produced by electrolysis using an external source of 14 V DC. The electrolyte consists of a 4% KOH solution in water. It was determined that electric power consumption for the production of HHO gas totals ~184 W/(l/min) and ~700 W was used to produce $V_{HHO} \approx 3.8$ l/min. The ratio between hydrogen and oxygen gas in HHO gas was 2:1, [109] supplying to the engine $V_{H2} \approx 2.5$ l/min and $V_{O2} \approx 1.3$ l/min. According to calculations, $B_{H2} \approx 0.0137$ kg/h of hydrogen and $B_{O2} \approx 0.1093$ kg/h of oxygen was supplied to the engine per hour. These gases mix with air supplied to the engine. Petrol is injected into the manifold ahead of the intake valve, and an engine electronic control unit is used to regulate its content depending on the set air/fuel ratio.

The tests were carried out with a 20% open throttle, with the crankshaft speed of $n = 2000$ rpm, which reflects the actual car operation conditions (the engine power P_B is 20 kW and this is enough to reach the speed of ~90 km/h). The composition of a fuel mixture was changed by regulating air/fuel ratio (lambda $\lambda = 1.0$–1.4). The tests were carried out using typical petrol fuel (EN 228) (labelled as petrol P_$\lambda = 1$; P_$\lambda = 1.1$; P_$\lambda = 1.2$; P_$\lambda = 1.3$; P_$\lambda = 1.4$) and petrol fuel with added $V_{HHO} \approx 3.8$ l/min HHO gas (labelled as petrol and hydrogen PH_$\lambda = 1$; PH_$\lambda = 1.1$; PH_$\lambda = 1.2$; PH_$\lambda = 1.3$; PH_$\lambda = 1.4$) (Figs. 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34 and 35). Changing air/fuel ratio, the hydrogen energy concentration in fuel mixture (C_{E_H2}) changed from ~0.77% at ($\lambda = 1.0$) to ~1.06% at ($\lambda = 1.4$).

By increasing air/fuel ratio and additionally supplying HHO gas, the speed of combustion of flammable mixture also changed [120]. In order to determine the impact of spark timing on energy and environmental engine indicators, the spark ignition timing Θ was regulated from 14° (crankshaft angle) CA before Top Dead Centre (bTDC) to 40° CA bTDC.

The key parameters of the tested fuel mixtures in the combustion process (φ_0—start of combustion; $\Delta\varphi_c$—combustion duration m_v—combustion intensity shape

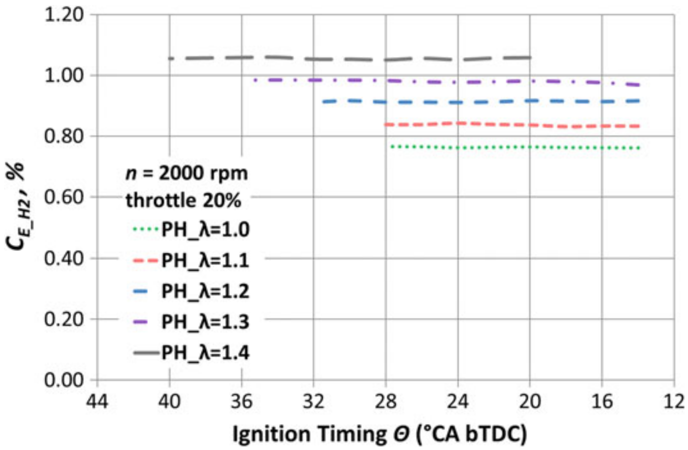

Fig. 24 Hydrogen energy concentration in fuel mixture

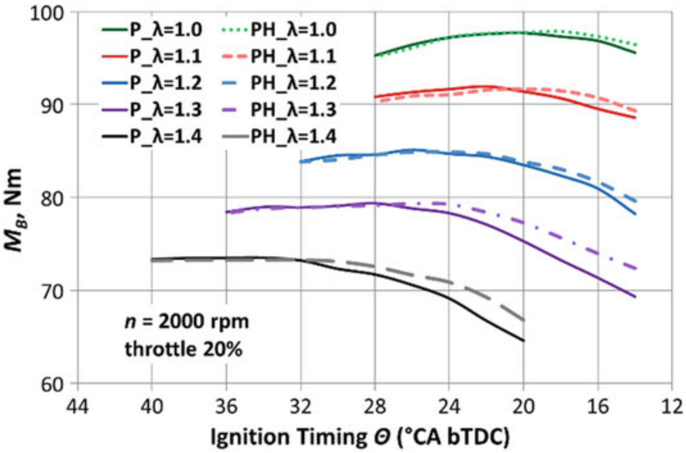

Fig. 25 Engine brake torque

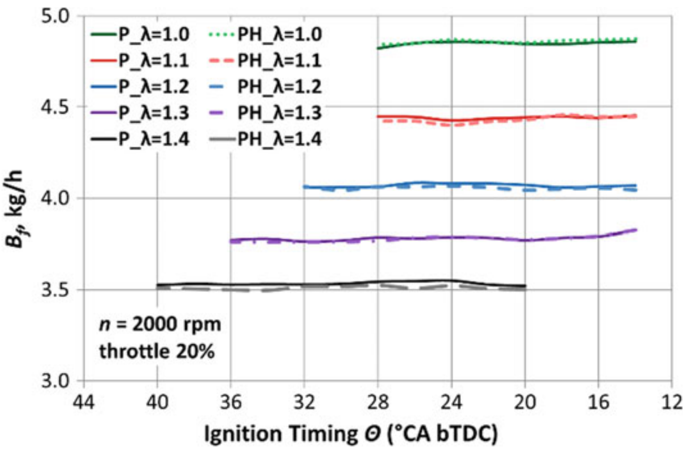

Fig. 26 Hourly fuel consumption

parameter) were determined using the AVL BOOST software (*BURN* app). These parameters are determined by developing a numerical model of the engine being tested and measuring heat release in the combustion process. Parameters measured during the experimental study were used in calculations: working cycle pressure in the cylinder p; cyclic injected fuel content m_{c_f}; cyclic aid content m_{c_air}, physicochemical fuel properties and others.

The stability of engine operation was assessed by analysing the maximum pressure (p_{max}) and indicates the mean effective pressure in the cylinder. The stability of the engine work depends on the change (variation) of these pressures. The more the pressure varies in the cylinder during combustion, the more unstable the operation

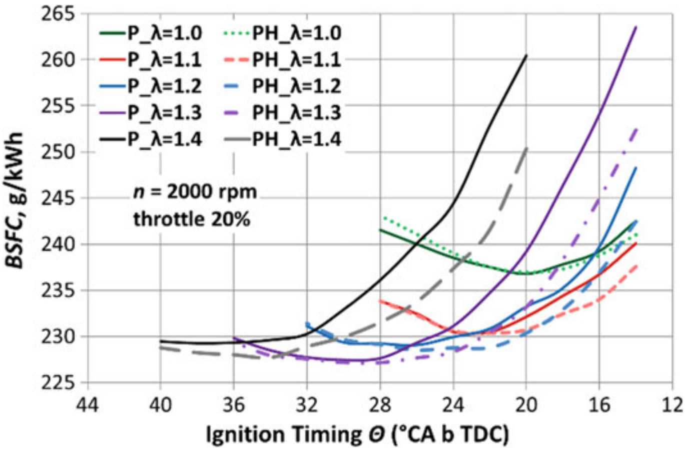

Fig. 27 Break specific fuel consumption

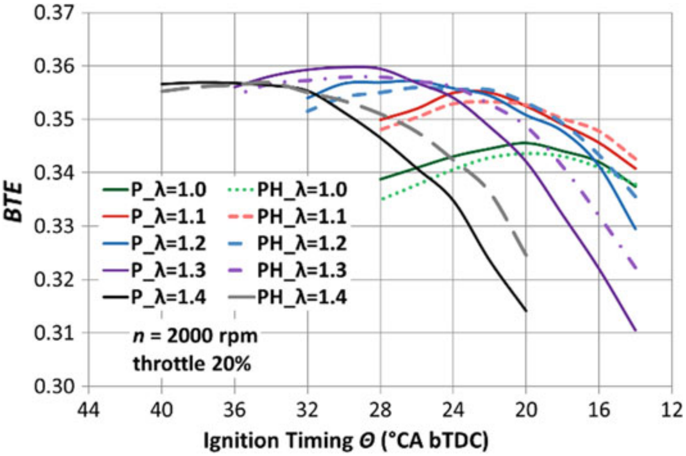

Fig. 28 Engine break thermal efficiency

of the engine is. In order to assess the stability of engine operation, the coefficient of variation of the Indicated Mean Effective Pressure of the engine $COV_{P_{imep}}$ is calculated [121, 122]. Numerical analysis of the combustion process and the calculation of $COV_{P_{imep}}$ was carried out with engine running on petrol (P) and petrol with added HHO gas (PH), at the fixed advance ignition angle $\Theta = 20°$ CA bTDC. $\Theta = 20°$ CA bTDC is optimal for an engine running of petrol with a 20% open throttle and seeking for the maximum torque M_B and *BTE*.

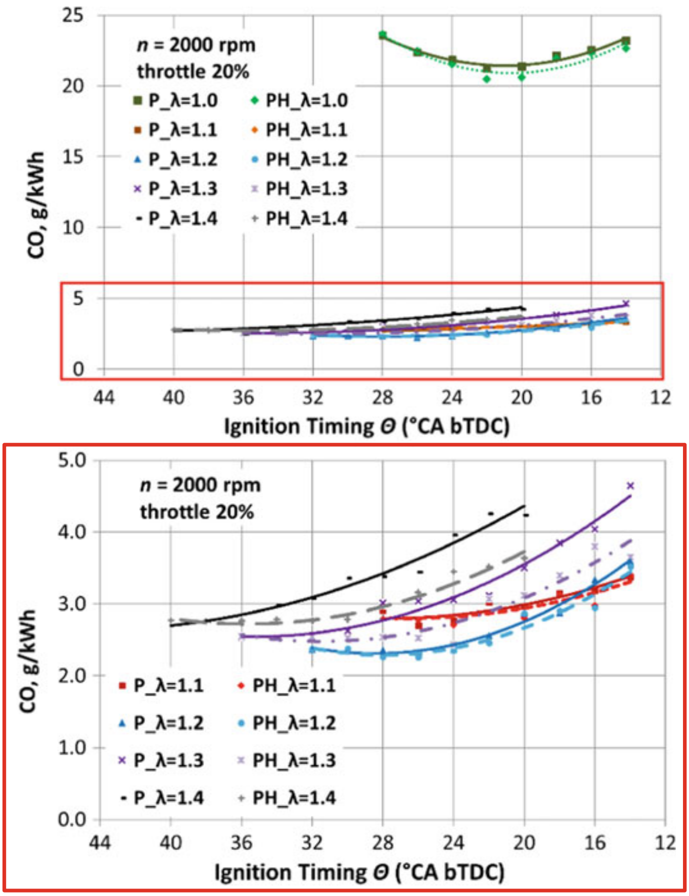

Fig. 29 Carbon monoxide CO emission of SI engine

6.2 *Spark Ignition Engine Energy Indicators*

With the engine running on petrol and stoichiometric fuel mixture (P_λ = 1), the maximum $M_B = 97.4$ Nm is achieved at the Advance Ignition Angle $\Theta = 20°$ CA bTDC (Fig. 25). When maintaining a fixed Advance Ignition Angle $\Theta = 20°$ CA bTDC and leaning the mixture, Brake Torque decreases to $M_B = 64.2$ Nm (−34.1%) (P_λ = 1.4). M_B decreases, because the leaning of the mixture gradually reduces the Hourly Fuel Consumption (B_f): from $B_f = 4.85$ kg/h (P_λ = 1.0) to $B_f = 3.52$ kg/h (−27.3%) (P_λ = 1.4), (Fig. 26). A proportionally lower amount of cyclic fuel (m_{c_f}) is injected in cylinders, emitting less heat during combustion. Brake torque also decreases (Fig. 27) due to a slower combustion of lean mixture: PH_λ = 1.1, $M_B = 91.1$ Nm (−6.5%); PH_λ = 1.2, $M_B = 83.4$ Nm (−14.4%); PH_λ = 1.3, M_B = 76.5 Nm (−21.5%); PH_λ = 1.4, $M_B = 65.9$ Nm (−32.4%).

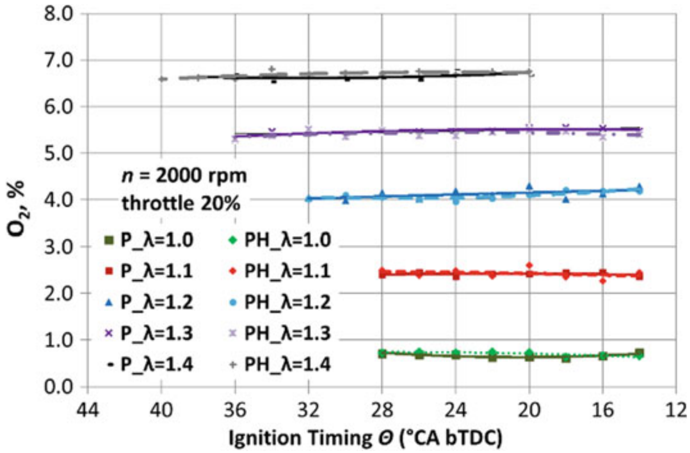

Fig. 30 Oxygen O_2 concentration in exhaust gases of SI engine

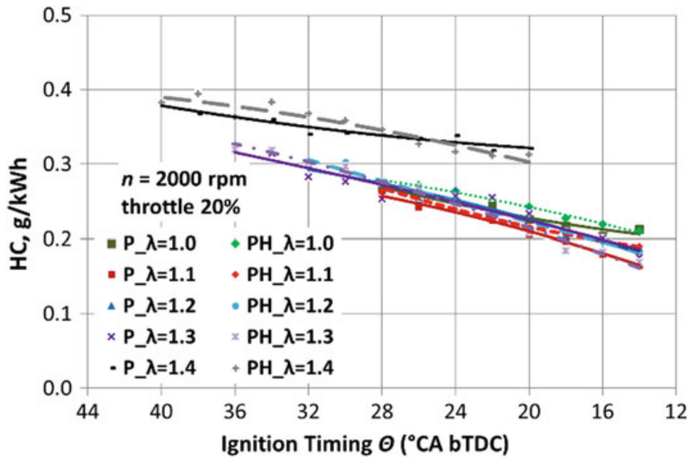

Fig. 31 Hydrocarbon HC emission of SI engine

Having advanced ignition timing, the leaning of a mixture results in a lower brake torque (Fig. 26): P_λ = 1.1, $\Theta = 22°$ CA bTDC, $M_B = 91.0$ Nm (−6.6%); P_λ = 1.2, $\Theta = 26°$ CA bTDC, $M_B = 84.7$ Nm (−13.1%); P_λ = 1.3, $\Theta = 28°$ CA bTDC, $M_B = 78.8$ Nm (−19.2%); P_λ = 1.4, $\Theta = 38°$ CA bTDC, $M_B = 72.8$ Nm (−25.3%). HHO gas additive allows for a lesser advancing of ignition timing to achieve the maximum brake torque: PH_λ = 1.1, $\Theta = 20°$ CA bTDC, $M_B = 91.1$ Nm (−6.5%); PH_λ = 1.2, $\Theta = 24°$ CA bTDC, $M_B = 84.5$ Nm (−13.3%); PH_λ = 1.3, $\Theta = 26°$ CA bTDC, $M_B = 78.6$ Nm (−19.4%); PH_λ = 1.4, $\Theta = 34°$ CA bTDC, $M_B = 72.8$ Nm (−25.3%).

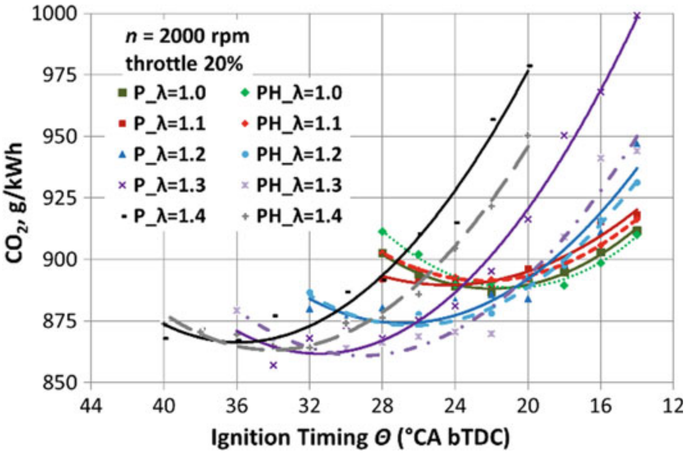

Fig. 32 Carbon dioxide CO_2 emission of SI engine

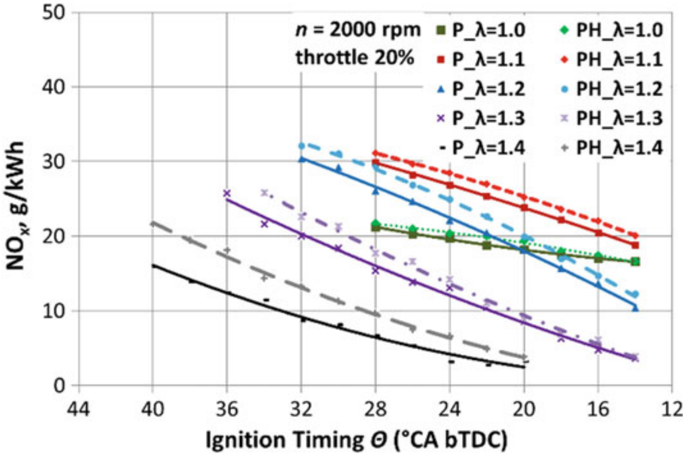

Fig. 33 Nitrogen oxides NO_x emission of SI engine

BSFC also depends on the engine power and fuel consumption [123]. With the engine running on petrol (P_λ = 1.0), the lowest *BSFC* = 236.8 g/kWh was achieved at the Advance Ignition Angle $\Theta = 20°$ CA bTDC (Fig. 27). When maintaining the fixed $\Theta = 20°$ CA bTDC and leaning the petrol–air mixture, the lowest *BSFC* value was achieved at λ = 1.1. At $\Theta = 20°$ CA bTDC and further leaning the mixture, a decline in *BSFC* was lower, and fuel consumption was increasing from λ = 1.3: P_λ = 1.1, *BSFC* = 232.1 g/kWh (−2.0%); P_λ = 1.2, *BSFC* = 233.4 g/kWh (−1.5%); P_λ = 1.3, *BSFC* = 239.2 g/kWh (+1.0%); P_λ = 1.4, *BSFC* = 260.5 g/kWh (+10.5%). When leaning the mixture and using HHO gas additive, a lower *BSFC* was achieved compared to P_λ = 1.0: PH_λ = 1.1, *BSFC* = 230.7 g/kWh (−2.6%);

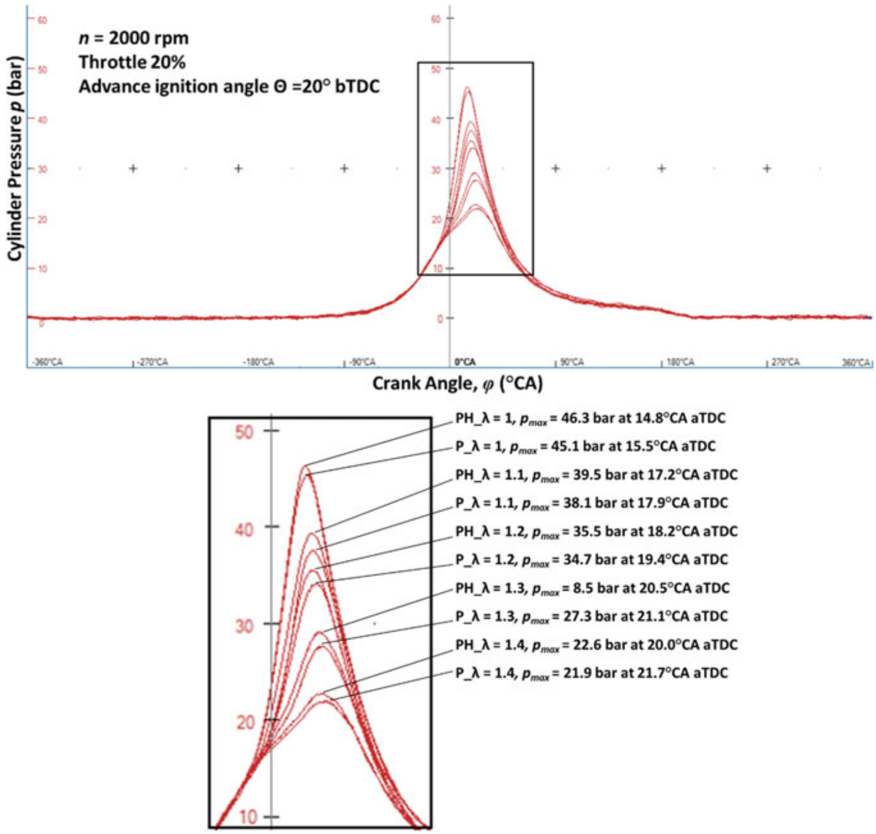

Fig. 34 Dependence of fuel pressure on cylinder pressure

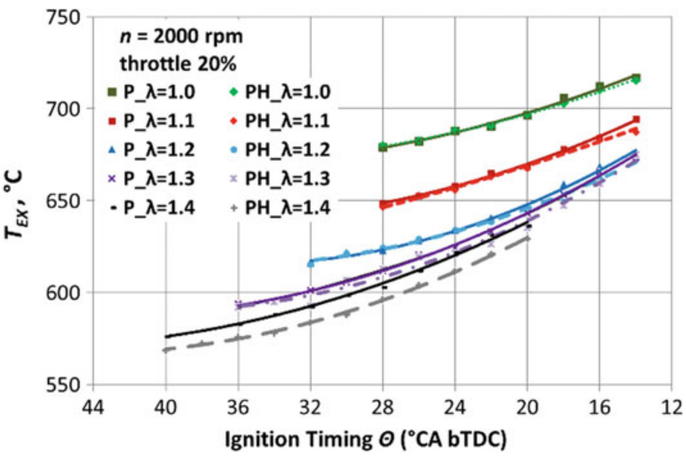

Fig. 35 Dependence of exhaust gas temperature on fuel composition

PH_λ = 1.2, *BSFC* = 230.4 g/kWh (−2.7%); PH_λ = 1.3, *BSFC* = 233.2 g/kWh (−1.5%); PH_λ = 1.4, *BSFC* = 250.4 g/kWh (+5.7%). Advancing ignition timing allows achieving better *BSFC* results: PH_λ = 1.1, $\Theta = 22°$ CA bTDC, *BSFC* = 230.5 g/kWh (−2.7%); PH_λ = 1.2, $\Theta = 26°$ CA bTDC, *BCFC* = 229.1 g/kWh (−3.3%); PH_λ = 1.3, $\Theta = 30°$ CA bTDC, *BSFC* = 227.6 g/kWh (−3.9%); PH_λ = 1.4, $\Theta = 34°$ CA bTDC, *BSFC* = 227.7 g/kWh (−3.8%).

BTE is affected not only by engine power and fuel consumption, but also by fuel *LHV*. A nearly three-times higher hydrogen calorific value, the supply of HHO gas ($V_{HHO} \approx 3.8$ l/min) into the engine and the leaning of a fuel mixture (λ = 1.0–1.4), the *LHV* of petrol and H_2 mixtures increased from 0.49 to 0.67% because of an increasing hydrogen energy concentration in fuel mixture (C_{E_H2}) (Fig. 24). With the engine running on petrol (P_λ = 1.0), the highest *BTE* = 0.346 was achieved at Advance Ignition Angle $\Theta = 20°$ CA bTDC (Fig. 28). By maintaining the fixed $\Theta = 20°$ CA bTDC and leaning the mixture: P_λ = 1.1, *BTE* = 0,353.1 (+2.0%); P_λ = 1.2, *BTE* = 0.351 (+1.5%); P_λ = 1.3, *BTE* = 0.342 (−1.0%); P_λ = 1.4, *BTE* = 0.314 (−9.1%). In stoichiometric mixture, hydrogen contained in HHO gas additive reduces engine efficiency, however, *BTE* indicators in leaner mixtures are better compared to P_λ = 1.0: PH_λ = 1.0, *BTE* = 0.344 (−0.6%); PH_λ = 1.1, *BTE* = 0.353 (+2.1%); PH_λ = 1.2, *BTE* = 0.353 (+2.1%); PH_λ = 1.3, *BTE* = 0.349 (+0.9%); PH_λ = 1.4, *BTE* = 0.325 (−6.1%).

The use of lean air–petrol mixtures and advancing the ignition timing allows achieving better engine efficiency results compared to P_λ = 1.0 and without the HHO additive: P_λ = 1.1, $\Theta = 22°$ CA bTDC, *BTE* = 0.355 (+2.7%); P_λ = 1.2, $\Theta = 26°$ CA bTDC, *BTE* = 0.357 (+3.3%); P_λ = 1.3, $\Theta = 30°$ CA bTDC, *BTE* = 0.360 (+4.1%); P_λ = 1.4, $\Theta = 38°$ CA bTDC, *BTE* = 0.357 (+3.3%). When using a HHO additive in lean mixtures, the maximum *BTE* is achieved having advanced the ignition timing by less than 2°–4° CA and compared to P_λ = 1.0, $\Theta = 20°$ CA bTDC, the following results were achieved: PH_λ = 1.1, $\Theta = 22°$ CA bTDC, *BTE* = 0.353 (+2.2%); PH_λ = 1.2, $\Theta = 24°$ CA bTDC, *BTE* = 0.35 (+3.0%); PH_λ = 1.3, $\Theta = 28°$ CA bTDC, *BTE* = 0.358 (+3.6%); PH_λ = 1.4, $\Theta = 34°$ CA bTDC, *BTE* = 0.357 (+3.3%).

6.3 Impact of Brown's Gas on Environmental Spark Ignition Engine Indicators

With the engine running on petrol and using a stoichiometric fuel mixture (petrol P_λ = 1), minimum carbon monoxide (CO) emissions (20.5 g/kWh) are achieved at the Advance Ignition Angle $\Theta = 20$–$22°$ CA bTDC (Fig. 29). When maintaining a fixed Advance Ignition Angle $\Theta = 20°$ CA bTDC and leaning the mixture, CO emission of incomplete combustion product decreases: P_λ = 1.1, ~3.0 g/kWh (−85.4%); P_λ = 1.2, ~2.75 g/kWh (−86.6%); P_λ = 1.3, ~3.55 g/kWh (−82.7%); P_λ = 1.4, ~4.45 g/kWh (−78.3%). CO reduction of incomplete combustion product was caused by excess oxygen: when changing the composition of combustible mixture from $\lambda = 1$ to $\lambda = 1.4$, the oxygen concentration in the exhaust gas increased by ~0.64 to ~6.7% (Fig. 30). The lowest CO emission (~2.75 g/kWh) was achieved at $\lambda = 1.2$, when O_2 concentration in exhaust gas was 4.2% (Fig. 30). The further leaning of the mixture resulted in increasing CO emissions because of decreasing combustion temperature and deteriorating oxidation process. HHO gas improves the combustion process with the engine running on lean mixtures and reduces emissions from 2.75 to 2.65 g/kWh (−3.6%) at $\lambda = 1.2$ CO, from 3.55 to 3.1 g/kWh (−12.6%) at $\lambda = 1.3$ and from 4.45 to 3.75 g/kWh (−15.7%) at $\lambda = 1.4$ CO.

Advancing the ignition timing for lean mixtures allows additionally reducing CO emissions, while HHO gas additive allows achieving this at a lower Advance Ignition Angle. The lowest CO emissions were achieved at ~2.3 g/kWh, petrol and hydrogen PH_λ = 1.2, $\Theta = 26°$ CA bTDC, and were ~88% lower than CO emissions from stoichiometric air–petrol mixture, because excess air and a ~3.3% lower Break Specific Fuel Consumption improve combustion (Fig. 27).

Emission of incompletely burned hydrocarbons (HC) ~0.26 g/kWh is achieved with engine running on petrol, stoichiometric fuel mixture (P_λ = 1) and at the P_λ = 1.1, the hydrocarbon oxidation improves and HC emission decreases to ~0.22 g/kWh (−15%). When further leaning the mixture, HC combustion starts deteriorating, and at P_λ = 1.4, HC emission increases to ~0.34 g/kWh (+30%). Advancing the ignition timing, HC emission increases with the engine running both on stoichiometric and lean mixture. HHO gas additive does not have any significant influence on HC emission.

Emission of CO_2 gases, which comprise greenhouse gases, mainly depends on fuel consumption, fuel chemical composition (C/H ratio) and the degree of completion of oxidation of carbon contained in fuel [124]. With the engine running on petrol and stoichiometric air–fuel mixture (P_λ = 1), the minimum CO_2 emission (~890 g/kWh) is achieved at the Advance Ignition Angle $\Theta = 20°–22°$ CA bTDC (Fig. 32). Leaning air–fuel mixture, at the Advance Ignition Angle $\Theta = 20°$ CA bTDC, CO_2 emission increases: P_λ = 1.1, ~895 g/kWh (+0.6%); P_λ = 1.2, ~893 g/kWh (+0.3%); P_λ = 1.3, ~920 g/kWh (+3.4%); P_λ = 1.4, ~977 g/kWh (+9.8%), the combustion process deteriorates and *BSFC* increases (Fig. 32). When additionally using HHO gas and leaving Ignition Timing the same, an increase in CO_2 emission is lower: PH_λ = 1.1, ~893 g/kWh (+0.3%); PH_λ = 1.2, ~890 g/kWh (0.0%); PH_λ = 1.3, ~893 g/kWh (+0.3%); PH_λ = 1.4, ~946 g/kWh (+6.3%). When using lean mixtures with HHO gas additive and advancing the Ignition Timing, CO_2 emissions decrease: PH _λ = 1.2, $\Theta = 26°$ CA bTDC, ~873 g/kWh (−1.9%); PH_λ = 1.3, $\Theta = 28°$ CA bTDC, ~861 g/kWh (−3.3%); PH_λ = 1.4, $\Theta = 34°$ CA bTDC, ~863 g/kWh (−3.0%).

With the engine running on petrol and stoichiometric fuel mixture (P_λ = 1.0), at the Advance Ignition Angle $\Theta = 20°$ CA bTDC, nitrogen oxide (NO_x) emissions were ~18 g/kWh (Fig. 33). Having leaned the mixture to P_λ = 1.1, NO_x emission increased to ~24 g/kWh (+33%), because free oxygen that does not take part in the combustion process forms in the combustion mixture, and the combustion temperature is high. When further leaning the mixture, even though more free oxygen is left after combustion, the combustion temperature and NO_x emissions decrease: P_λ

= 1.2, ~18 g/kWh (0.0%); P_λ = 1.3, ~8 g/kWh (−55%); P_λ = 1.4, ~3 g/kWh (−83%). HHO gas additive speeds up the combustion process and raises its temperature; compared to P_λ = 1, NO_x emission at the Advance Ignition Angle $\Theta = 20°$ CA bTDC is: PH_λ = 1.0, ~19 g/kWh (+5%); PH_λ = 1.1, ~25 g/kWh (+40%); PH_λ = 1.2, ~20 g/kWh (+11%); PH_λ = 1.3, ~9 g/kWh (−50%); PH _λ = 1.4, ~4 g/kWh (−78%). When increasing the Advance Ignition Angle, NO_x concentration increases, however, at the lowest *BSFC* (Fig. 35), NO_x emission is lower compared to P_λ = 1, $\Theta = 20°$ CA bTDC, ~18 g/kWh: PH_λ = 1.3, $\Theta = 28°$ CA bTDC, ~18 g/kWh (0.0%); PH_λ = 1.4, $\Theta = 34°$ CA bTDC, ~15 g/kWh (−17%).

6.4 Change in Spark Ignition Engine Combustion Process Using Brown's Gas Additive

The SI engine's combustion process analysis was conducted at a 20% opened throttle, at the crankshaft speed of $n = 2000$ rpm. Advance Ignition Angle $\Theta = 20°$ CA bTDC, the maximum Brake Torque M_B is reached at this point with *BTE* engine running on petrol when P_λ = 1.0 (Figs. 25 and 29). With gradually leaning the mixture from λ = 1.0 to λ = 1.4, the maximum pressure in the cylinder gradually drops from 45.1 bar to 21.9 bar (−51%) (Fig. 34). Having reached the maximum pressure, the position of the crankshaft changes from 15.5° CA aTDC to 21.7° CA aTDC (6.2° CA). HHO gas additive speeds up a slower combustion of lean mixture ($V_{HHO} \approx 3.8$ l/min). Having leaned the mixture to PH_λ = 1.4, the maximum pressure decreases to 22.6 bar (the difference of ~0.7 bar compared to P_λ = 1.4). The maximum pressure is reached closer to—20.7° CA aTDC (a difference of ~1.7 CA compared to P_λ = 1.4).

The hydrogen contained in HHO gas speeds up the combustion of lean mixture. This is confirmed by measurements of temperatures of exhaust gas (Fig. 35). When leaning the petrol–air mixture from P_λ = 1.0 to P_λ = 1.4, having set the Advance Ignition Angle $\Theta = 20°$ CA bTDC, the temperature of exhaust gases decreases from 697 to 637° C (−8.6%), because less fuel is supplied to the cylinder (Fig. 26) and M_B of the engine decreases. However, using HHO gas additive (PH_λ = 1.4), the temperature of exhaust gases decreases even more, to 629° C (−9.8%), even though the engine's M_B increases. This shows a positive HHO gas impact in speeding up the combustion, when air–fuel mixture is leaned and combustion slows down.

Having measured pressure in the cylinder, *IMEP*, which directly affects engine Brake Torque and Power, was calculated. Having leaned the mixture from P_λ = 1.0 to P_λ = 1.4, *IMEP* declines from 0.905 to 0.644 MPa (−29%) (Fig. 36). HHO gas additive allows partly compensating *IMEP* reduction, by using PH_λ = 1.4 (*IMEP* = 0.662 MPa).

COV IMEP, which is determined by analysing pressure in the cylinder in 100 cycles, is used to assess the stability of ICE indicator pressure. With engine running on stoichiometric mixture (λ = 1.0), HHO gas reduces the *COV IMEP* from 0.0239 to 0.0219 (−8.4%) (Fig. 36). When leaning the mixture to λ = 1.4, combustion stability

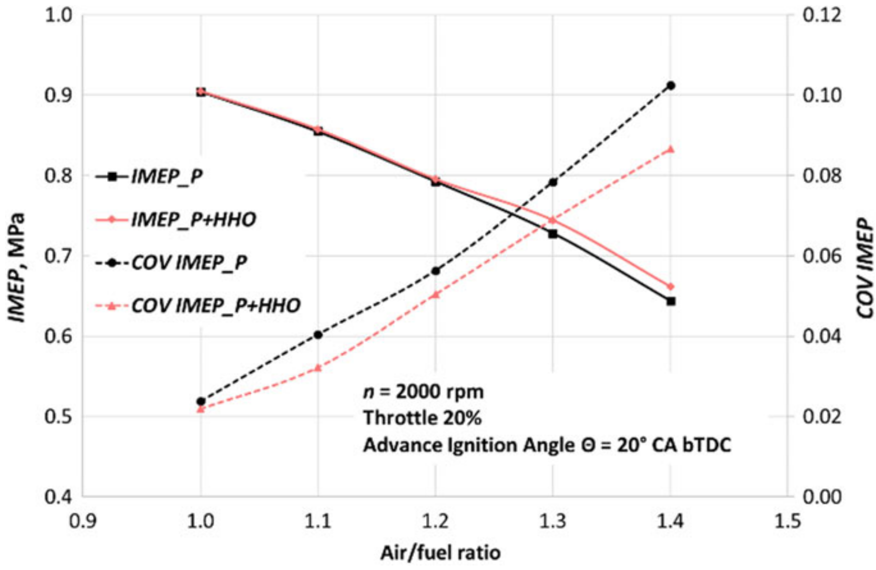

Fig. 36 *IMEP* and *COV IMEP* dependence on fuel composition

decreases and *COV IMEP* increases to 0.1025. Additionally, supplying HHO gas (PH_ $\lambda = 1.4$), *COV IMEP* decreases to 0.0866 (−15.5%), which shows that HHO gas has a more significant positive impact on ensuring the stability of combustion on leaner air–petrol mixtures.

The use of low amount of H_2 gas additive in SI engine, additionally supplying HHO gas may also have an energy and environmental impact with engine running on fuel mixtures, which are less flammable and have a lower combustion speed.

7 Conclusions

1. Reducing permissible levels of CO_2 emissions from cars does not guarantee a reduction in overall CO_2 emissions, whereas, as the vehicle fleet continues to grow and aging, global CO_2 emissions from the transport sector are even increasing.
2. At present, the most effective and socially least sensitive means of reducing the concentration of CO_2 emissions from private cars is the carbonless additives such as hydrogen to conventional fuels of ICE. This would not essentially change the behaviour of people (drivers) and the refuelling system (infrastructure).
3. The number of electric cars has been steadily increasing not only as a result of political and economic incentives, but also of constant environmental education of residents, the ability to use their own and public charging stations.

The legal framework for promoting electric cars allows for a smooth transition from engines running on conventional fuels to alternative, mostly electric, powertrains.

4. The use of low-carbon fuels has been promoted and constantly developed, which leads to the new biofuel production generation aimed at searching for new sources of raw materials rather than increasing production efficiency only.
5. The biofuel strategies used allow choosing the most appropriate type of production of biofuel in a particular region and providing for respective production development trends.
6. The trends of use of bio-hydrogen as the 4th generation biofuel is most promising. Its new production trends show opportunities to produce bio-hydrogen at a relatively low price using respective enzymes, CO_2 and light.
7. Conventional and alternative sources of energy may be used in the production of hydrogen, separating carbon compounds. Hydrogen is a carbonless fuel and its combustion generates neither CO_2 nor soot. This comprehensively reduces Greenhouse Gas emissions.
8. Hydrogen is a carbonless fuel; it does not produce CO_2 and particulates PM when burned. This reduces GHG emissions in a complex way.
9. In a spark ignition engine, hydrogen can be used pure or as a petrol additive. In SI engines running on natural gas, hydrogen may be used as an additive to these gaseous fuels. In a compression ignition engine, hydrogen can be used as an additive to fuels (diesel, biodiesel), using liquid fuel for ignition.
10. By supplying hydrogen to the SI engine intake manifold, hydrogen takes up a relatively large volume which impairs cylinder volumetric efficiency and reduces engine power. Hydrogen injection directly into the cylinder increases of the engine power thanks larger heating value of the air-hydrogen mixture.
11. Compared to other spark ignition engine fuels, the flammability range of the hydrogen and air mixture is very wide, the combustion temperature of the lean mixture is lower, which reduces NO_x emissions. Higher *BTE* is achieved when the ICE engine is running on the leaner mixture.
12. The low amount of energy required to ignite hydrogen causes auto ignition problems. This is noticeable in CI engines with higher compression stroke end temperatures. The problem of hydrogen uncontrolled auto ignition can be solved by proper cooling of the intake air into the cylinder.
13. The addition of hydrogen can reduce the intensity of heat release and reduce NO_x emissions of compression ignition engines. Smoother combustion and lower C/H ratio reduce CO_2, CO and HC emissions.
14. Using the current of car's electric generator, it is possible autonomously produce a mixture of hydrogen and oxygen by electrolysis called Brown's gas, designated HHO. 1/3 of the HHO gas volume is O_2 and 2/3—H_2 gas. Generator of 700 W power produces 3.8 l/min HHO gas (2.5 l/min H_2). This amount of hydrogen additive provides approximately 1.0% of the fuel energy, 99% of the energy is supplied by petrol when the engine develops 20 kW.
15. By making the fuel mixture leaner ($\lambda = 1.2$–1.3) and using the Brown's gas additive, CO emissions are reduced to approximately 80%, CO_2 and CH emissions

are low, and NO_x emissions can be reduced to 55% ($\lambda = 1.3$). For maximum *BTE* and early ignition timing, CO and CO_2 emissions decrease, when at that time hydrocarbon HC and nitrogen oxide NO_x emissions increase.

16. Brown's gas additive increases combustion stability in spark ignition engine. When the engine is running at stoichiometric combustible mixture, *COV IMEP* reduced by approximately 8%, and with lean mixture (petrol and hydrogen $\lambda = 1.4$), Brown's gas additive reduces *COV IMEP* by ~15%.
17. It is validated by ICE bench tests that hydrogen and/or its additives are one of the most readily available and effective carbonless substitutes of internal combustion engine fuels.

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The Gaseous Fuels Towards Contemporary Economic and Ecological Challenges

Marek Flekiewicz, Grzegorz Kubica and Paweł Fabiś

Abstract Alternative fuels play a key role among many directions of action taken in implementing climate change-related activities. The search for clean, low-carbon and renewable motor fuels is one of the main directions of research and development conducted worldwide. This study discusses issues regarding the use of selected gaseous fuels to power motor vehicles, i.e. hydrogen (H_2), hydrogen-methane mixtures (HCNG) and dimethyl ether (DME). Also presented are the results of research on the use of gas fuel mixtures that ensure the efficiency of energy conversion and contribute to reducing emissions.

Keywords Hydrogen · Methane · DME · Gaseous fuels · IC engine · Fuel cell

1 Advantages of Alternative Fuels Using

Transport is not the main source of greenhouse gas emissions; it only contributes to around 22% of total CO_2 emissions associated with energy production and processing. However, it plays an important role primarily due to the rapid increase in traffic and almost complete dependence on fossil fuels. Also, the development of transport, which is the fastest-growing economic sector among all emission sources, cannot be considered sustainable. Local air pollution (particulate matter, ozone), climate change, traffic jams, land use, accidents, and noise are becoming a major problem today and are increasingly regulated worldwide. Besides, the development of transport is accompanied by increasing demand for fuel, and consequently an increase in

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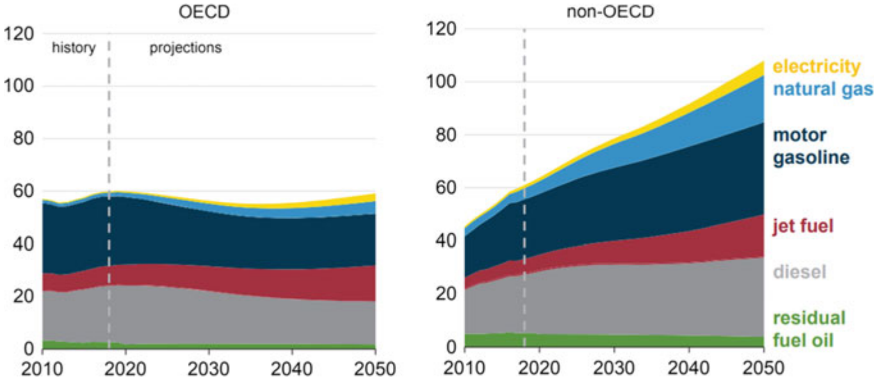


Fig. 1 Transportation energy consumption in quadrillion British thermal units Btu = 1055 kJ [1]

greenhouse gas emissions (Fig. 1) [1]. According to the latest ITF data, CO_2 emissions from passenger transport around the world will increase from 30 to 110% by 2050 (ITF Transport Outlook 2015), depending on fuel prices and the development of urban transport [2]. Thus, the role of the transport sector in the implementation of activities related to climate change and sustainable development is fundamental.

The adoption of the Paris Agreement has allowed paving the way to mitigate climate change and establishing a five-year review cycle for national decarbonization commitments from 2020. These commitments set out two main areas of strategic action in transport. The first one includes activities aimed at balancing the development of transport systems and mobility management, the second one in the field of increasing the efficiency of energy processing by improving the design of means of transport and introducing low-carbon and clean energy carriers. Activities in the first area, such as transportation demand management—TDM and mobility management—MM have been implemented successfully in many countries for several years. Urban transport development, traffic restrictions and city taxes, parking prices, shifting transport from private car to public transport, using EcoDrive, implementing Park and Ride systems, car sharing, replacing a car with a bicycle or a walk, moving freight from roads to railroad tracks, as currently very popular activities bring the expected results much faster than activities in the second area.

The improvement of vehicle construction and the introduction of low-carbon and clean energy carriers, as the basic activities in this area, need the support of both governments and the entire industry associated with the production of means of transport. Only the right policies, standards, and mechanisms favoring environmental protection can contribute to faster implementation of pro-ecological solutions in means of transport.

The energy consumption forecast up to 2050, prepared by the EIA, indicates that measures are taken in the EOCD countries to gradually reduce emissions stabilize the demand for energy carriers used in transport (Fig. 1). However, the increasing

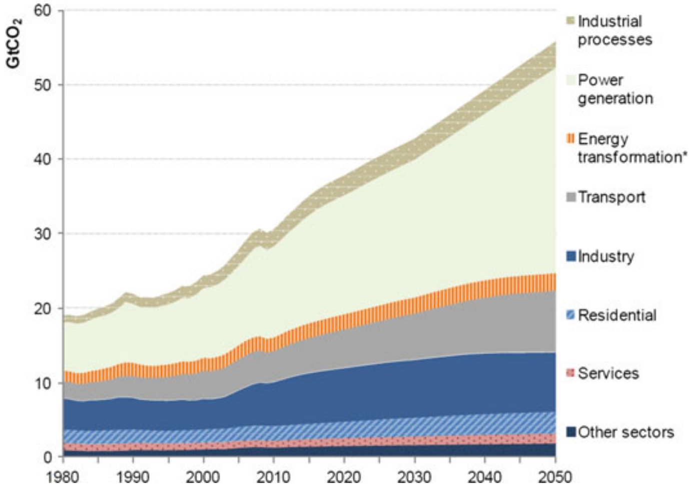


Fig. 2 Global CO_2 emissions by source: Baseline, 1980–2050 [1]

demand for energy carriers in developing non-member countries contributes to the global increase in predicted CO_2 emissions (Fig. 2).

Currently, European Union countries are responsible for around 83% of total greenhouse gas emissions, mainly due to the ever-increasing demand for road transport. It is expected that the introduced CO_2 emission limits will at least ensure the stabilization of energy demand. On the other hand, fees for exceeding the allowable emissions are already mobilizing manufacturers to make changes in the design of vehicles and their propulsion systems (Fig. 3). Increasing the efficiency of energy conversion contained in the fuel is possible as a result of limiting the losses in its processing (Fig. 4). Reduction of vehicle weight, reduction of aerodynamic drag, improvement of combustion engine efficiency, hybridization and the use of low carbon fuels, such as biofuels, hydrogen, liquefied petroleum gas (LPG) or natural gas (compressed CNG and liquefied LNG), development of drives electrical are the main paths for pro-ecological construction and technological development of transport means.

Alternative fuels have become an attractive option to counteract the effects of emissions from combustion engines. Various experimental works are carried out by scientists who choose substitute fuel that can be cost-effective from an environmental point of view. The closest solution is biodiesel, bio alcohol, methanol, propanol, ethanol, butanol, biomass, biogas, natural gas, dimethyl ether (DME), hydrogen (H_2) and much more to be discovered in the future. Among above Hydrogen and natural gas are widely recognized as clean energy carriers; moreover, both are common and easy to obtain.

Actions necessary to improve the energy conversion efficiency of motor vehicles, and consequently also tailpipe emissions, are very generally presented in Fig. 4. An important factor affecting greenhouse gas emissions is also the type of energy

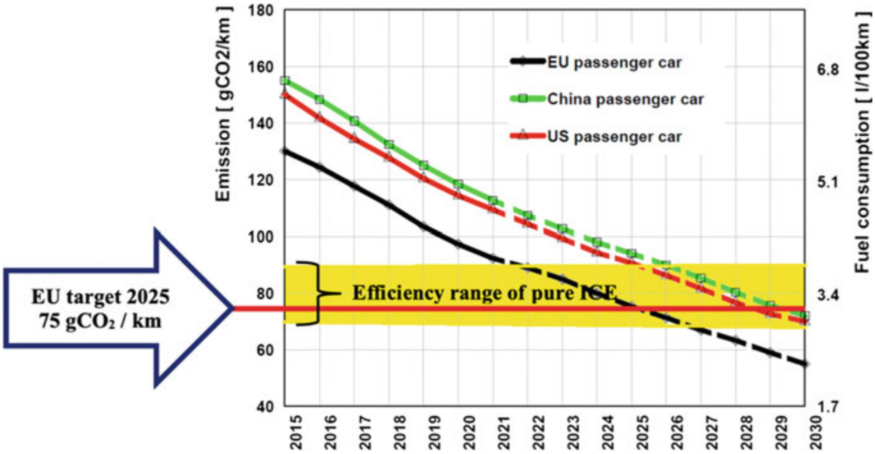


Fig. 3 Historic and projected changes in CO_2 emissions and fuel consumption over time. The figure also describes the possible achievable IC efficiency and EU limit of CO_2 emission in 2025 [60]

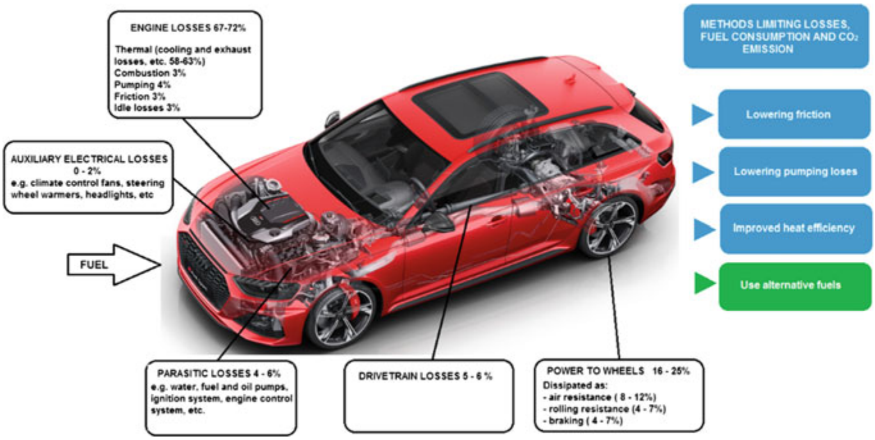


Fig. 4 Energy requirements for combined city and highway driving [60]

carrier used to power the vehicle, consequently affecting the increased interest in low-carbon fuels. Variation over time of the hydrogen-to-carbon atomic ratio (H/C) in the world's fuel mix are presented in Fig. 5 [3]. The decreasing share of coal in fuels visible after 2000 is caused by using alternative gaseous fuels, including DME, mixtures of Methane, and Hydrogen, as well as Hydrogen itself.

Higher values of the hydrogen-to-carbon atomic ratio, conducive to reducing CO_2 emissions, technical options for adapting vehicles to drive these fuels are the main reasons for using alternative fuels. These fuels also contribute to the diversification of

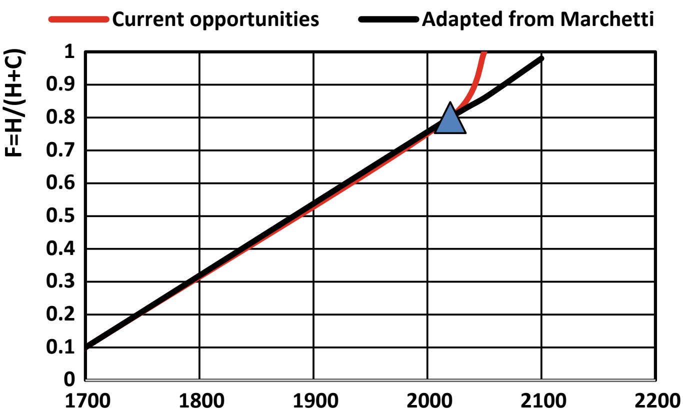


Fig. 5 Variation over time of the hydrogen-to-carbon atomic ratio (H/C) in the world's fuel mix, in terms of the ratio H/(H + C). The ratio H/C is approximately 4 for natural gas, 2 for petroleum, 1 for coal and 0.1 for wood. The triangle denotes the point at which H/C = 4 [61]

fuels used to power vehicles and are included in the production plans of manufacturers of vehicles (Fig. 6).

These essential advantages of alternative fuels formed the basis for preparing this study. The authors present the scope of the conducted research, discussing the possibilities of using hydrogen, a mixture of hydrogen and methane (HCNG), and DME as energy carries for vehicles' power sources.

2 Current Status and Perspectives of Using Methane-Based Fuels

2.1 Natural Gas as an Energy Carrier

Natural Gas (NG), is currently one of the basic energy sources in the global economy, with the possibility of a very wide use, also as a fuel in internal combustion engines. It owes its name to its origin because it occurs in the earth's crust in the form of free gas (dry), or in the form of hydrocarbon hydrates (wet).

The basic component of natural gas is methane (CH_4), whose share is usually above 90% (Fig. 7). The rest are further simple hydrocarbons in the series, and depending on the conditions of occurrence, trace amounts: CO_2, H_2, N_2, H_2S and noble gases. Characteristic for the presence of natural gas dissolved in groundwater is sulfur pollution. This is called sour type.

The strategic importance of natural gas has been gradually increasing in recent years. Many factors make the high priority of using this energy carrier. Some of them have already been noticed and are now well known. But progressive economic

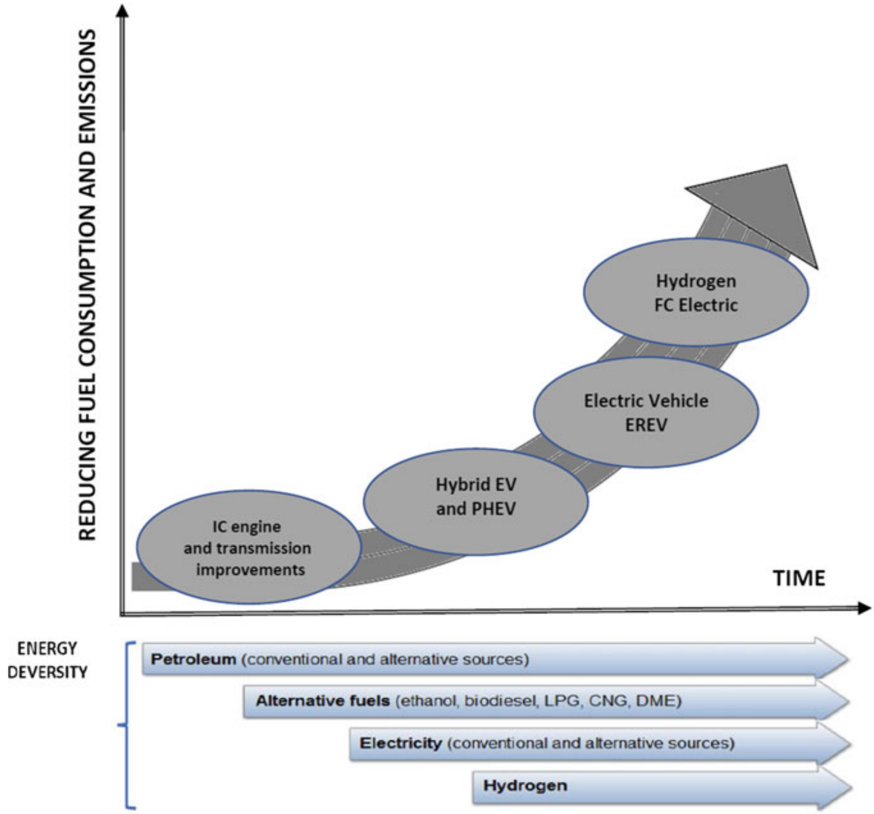
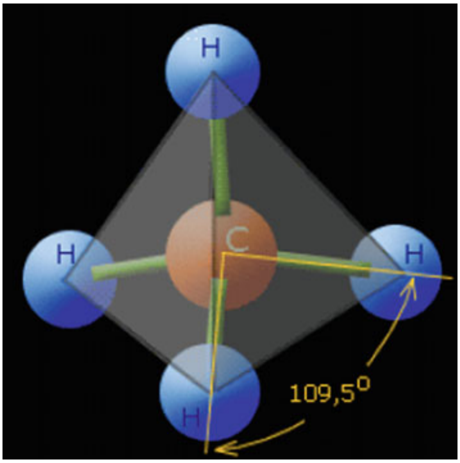


Fig. 6 GM's advance propulsion strategy [62]

Fig. 7 Methane molecule [63]



development and political and social changes are constantly discovering new aspects of using this fuel. They are constantly confronted with the general criteria that should be met by alternative fuel placed on the market. Of the known benefits of using natural gas as fuel, the most significant relate to ecological issues. Due to the requirement to meet relevant standards, the level of toxic compounds emission in the products of combustion of this fuel is of key importance. This is due to the fact that natural gas does not contain complex hydrocarbons or carcinogens. Reduced CO_2 emissions are clearly visible in combustion products. The exhaust gases are free from the solid waste of combustion (dust, soot, etc.). The extraction and distribution processes take place in conditions that do not cause a particularly negative impact on the environment.

The basic form of using natural gas as fuel in internal combustion engines is the installation of a compressed natural gas supply, commonly referred to as CNG. The fuel is stored in the tank at a pressure of 20–26 MPa, which makes it possible to concentrate more than 200 times the energy stored on the vehicle. The energy value of 1 Nm^3 of gas is approximately equal to 1 dm^3 of gasoline or diesel. As motor fuel, natural gas has been present in the automotive industry since 1860 and is used in both SI and CI engines. However, the intensive development of this fuel supply system began in the 1980s and continues. The feeding systems used underwent many structural transformations during this period. From simple mixer systems to the currently used, electronically controlled multi-point injection. Significant changes also took place in the construction of compressed gas tanks (Figs. 8 and 9). Currently, two basic solutions are used: thick-walled steel cylinders or lighter composite tanks.

Fig. 8 Historical tanks for natural gas [63]

Fig. 9 Steel cylinders CNG, $p_{max} = 20$ MPa

An alternative form, due to the way fuel is stored, are LNG installations. Fuel is stored in the liquid phase. The phase transition occurs by cooling natural gas to a temperature below −162 °C. This solution results in a 630-fold reduction in fuel volume, but maintaining such conditions requires the use of a special cryogenic tank. Its design consists of an inner vessel and an external reservoir that merge into the flange part. A vacuum is created in the space between their walls, which ensures proper thermal insulation (Fig. 10). These types of solutions are increasingly used, primarily in trucks and buses. LNG systems are also used in maritime transport.

2.2 Features of the Combustion of a Methane in SI Engine

Due to the current specifics of using gas systems to feeding IC engines, where they are usually installed as alternative systems, the obtained parameters and observed phenomena are generally compared with the indicators and processes characteristic of gasoline as the base fuel. The general conclusions made as a result of comparing these fuels clearly signal two basic problems that accompany the burning of natural gas.

The first of these is a clear reduction in the value of utility indicators. When changing fuel from gasoline to natural gas, a decrease in engine power is observed, on average 8–12%, depending on the power supply system used [4–6]. This change is caused first of all by the lower calorific value W_u of the air-gas mixture produced.

Fig. 10 Cryogenic LNG tank mounted in the truck [64]

Another reason is the higher La value, which means that the amount of fuel in a given volume filled with the mixture decreases. In addition, when using alternative installations, a decrease in the volumetric efficiency of the engine is also often noted. As a consequence of these changes, under the same control and load conditions of the engine, the charge portion supplied in each cycle to the combustion chamber contains less energy. Another reason for the reduction in power are differences in the combustion process. It is generally known that the combustion of natural gas in the engine is of a chronic nature. It is also justified by the results of the bench tests (Fig. 11) [7].

In the example presented, it can be observed that in the case of natural gas supply the largest differences are observed during the initiation period of the combustion process. Although further heat evolution is as intense as in the case of gasoline, the effect of chronic combustion at the initial stage of the process is a lower pressure build-up. The maximum pressure value is also lower, because the main phase of the combustion process falls in this system for the period when the piston movement causes the volume of the combustion chamber to increase and the load gradually expands.

Unfavourable phenomena illustrated in the example above are a kind of challenge that should be addressed when looking for solutions in such an organization of the process of energy processing in the engine so that it is possible to increase its overall efficiency, while using the advantages of ecological fuels with reduced carbon content.

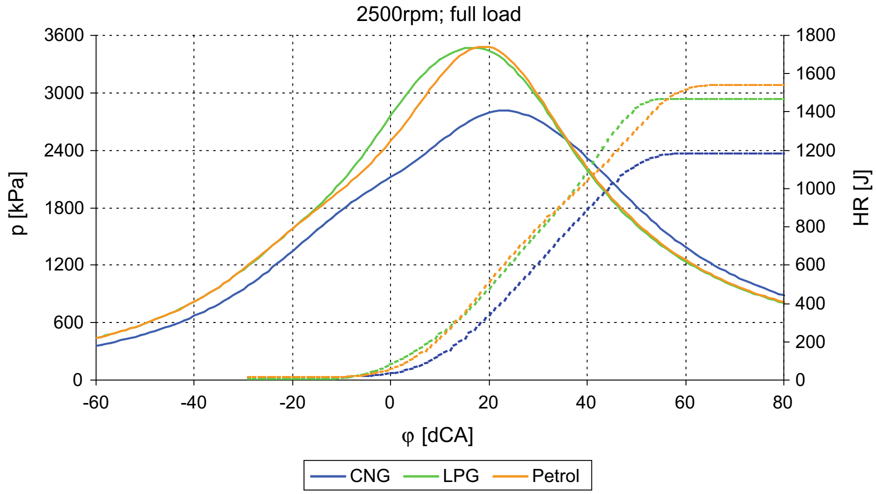


Fig. 11 Changes in indicated pressure and heat release for various fuels [7]

2.3 Methane Enrichment with Hydrogen

The ideal fuel in ecological terms is hydrogen, because its combustion products do not contain carbon compounds and hydrocarbons. It can be used in compressed form—H_2, or liquefied—LH_2. However, its widespread use is not yet profitable. In practice, there are currently a number of technical and technological problems that prevent the efficient use of this energy carrier [8, 9]. Hydrogen is an explosive gas, and its storage and distribution require the use of special metal alloys as structural materials for plant components. Due to the low molecular weight (small particle size), it is a highly penetrating gas, which is why fittings used in hydrogen installations require special sealing technology.

However, the real solution becomes the use of hydrogen fuel blends with natural gas, because this form of use gives the possibility of obtaining fuel with an even lower carbon content, compared to conventional petroleum fuels. In addition, increasing the proportion of hydrogen in a blend with natural gas, even up to 50% in volume, does not increase the risk of explosion and does not require the use of special materials in the construction of infrastructure elements. There are applications that use this type of fuel in SI engines. Gaseous fuel, abbreviated as HCNG, is a blend of compressed natural gas with the addition of hydrogen, in the order of 4–9%. In some countries, special routes are created along which HCNG refuelling stations are located [10]. In the United States there is also a known system called HYTHAN® (HYdrogen + meTHAN), which is designed for diesel engines. This system assumes dual fuel Hythan + Diesel. The volume of hydrogen in the fuel changes by up to 20%. The average energy share is 5–7%. This solution allows reduction of diesel fuel consumption in the range of 50–70%, and also limits NO_x emissions up to 60% [11].

The examples cited show new possibilities in the use of alternative fuels. A significant practical advantage here is the possibility of using existing CNG feeding systems, as this eliminates the need to create a new, separate system. An important argument stimulating the development of the described power supply is the possibility of obtaining economic benefits resulting from a lower fuel price. Therefore, there is a need to conduct scientific research and gather experience that will allow for proper interpretation of phenomena occurring in the engine in the process of energy conversion with the use of a new type of fuel.

The analysis of the existing scientific and research achievements in the scope of the possibility of using hydrogen as an independent fuel, or in the form of blends CH_4/H_2 or HCNG, presents broad perspectives of using this gas in the supply of internal combustion engines. In several centers, tests of hydrogen-powered engines, in addition to ecological values (exhausts without carbon compounds), indicate at the same time a much higher efficiency of the engine compared to gasoline [12–16]. Research conducted in the team of Sierens et al. [17] on a 4-cylinder engine with a capacity of 1.8 dm^3, showed an increase in thermal efficiency by up to 60%, compared to the results obtained with gasoline.

However, the widespread use of this fuel at the current stage of development of hydrogen feeding systems faces a number of problems. The main obstacles relate to the method of hydrogen storage on the vehicle and control of the energy conversion process [9, 18, 19]. What is needed above all is a new strategy to control the composition of the mixture, which will allow reducing the NO_x content in combustion products [20–24].

In the context of the presented situation, the use of hydrogen as an additive to commonly used fuel gains additional value, for which technical aspects were known and mastered. One of the first who took this direction in scientific research were Stebar and Parks [25], and Varde [26]. Presenting the results of their research, they emphasized the possibilities of enriching the used fuels with hydrogen in order to use the advantages of this energy carrier. In 1983, B. Nagalingam and his team published the results of research on a research engine powered by blends of HCNG, where the attention was drawn to the fact that the engine power was reduced with the increasing share of hydrogen, but at the same time the possibilities of extending the range of combustion of lean mixtures were noticed [27]. Combining energy and ecological profiles, G. A. Karim and his team formulated the theoretical foundations for using hydrogen in a blend with methane [28]. Since then, research on the use of methane-hydrogen blends has been intensively conducted in several research centers around the world. The results obtained confirmed the theses formulated in the first papers [29], which assume the possibility of improving the parameters of the methane combustion process by using hydrogen. Positive, convergent in essential issues, results of research in this field were obtained in independent institutions [30–33]. A strong argument motivating the adopted solution is to compare the physicochemical properties of the fuels in question (Table 1); including hydrogen, where special attention is paid to those features that cause adverse effects when burning CNG, or pure methane.

Common conclusions from these studies indicate as the main benefits:

Table 1 Physicochemical properties of selected fuels [36, 72]

Feature	Hydrogen	Methane	Petrol
Air-fuel ratio lower limit	~9	~1.9	~1.4
Range of burning (% gas volume in air)	4–75	5.3–15.0	1.2–6.0
Minimal ignition energy (mJ)	~0.02	~0.28	~0.25
Burning speed (m/s)	~2.90	~0.38	~0.37 to 0.43
Adiabatic flame temperature (K)	~2318	~2190	~2470
Selfignition temperature (K)	~858	~813	~500 to 750
Density (kg/m^3) at 293.15 K and 101.3 kPa	0.082	0.717	4.4
Stoichiometric air to fuel ratio (kg/kg)	~34	~17.2	~14.8
Volumetric lower heating value (MJ/kg)	~3.37	~2.56	~2.79
Mass lower heating value (MJ/kg)	~120	~50	~44.5

- reduction of burning time due to increased burning speed; both during the initiation period (MFB = 0–10%) and during the effective combustion period (MFB = 10–90%),
- significant reduction of CO_2 and CO emissions,
- increasing the overall efficiency of the engine—blends with a volume fraction H_2 = 10–30%.

Specific application solutions mainly apply to SI engines, but concepts for CI engines have also been presented [75, 76]. An example is a dual-fuel engine solution where a mixture called Hythan is fed to the combustion chamber by direct injection. The main benefits relate to reduced base fuel consumption, carbon emissions and particulate emissions.

The analysis of the results of experimental and simulation tests carried out in the field of the use of low-carbon gaseous fuels with increased hydrogen content shows that, thanks to its properties, it is possible to burn the engine more efficiently while ensuring the appropriate quality of combustion products. Ongoing research, mainly in the area of CH_4/H_2 blends, reveals new areas of their application. The presented results are, however, limited to the vast majority to present the values of engine performance indicators and exhaust emissions. Therefore, there is a need for a detailed analysis of changes taking place so that the directions of impact depending on the composition of the fuel used can be indicated more precisely.

2.4 *Properties of a Combustible Mixture Based on Methane-Hydrogen Blends*

The increase in the share of hydrogen in the blend primarily affects the composition of the fuel (Fig. 12). The molecular weight of the fuel is calculated depending on the methane/hydrogen ratio, taking the molecular weight of the fuel components: CH_4

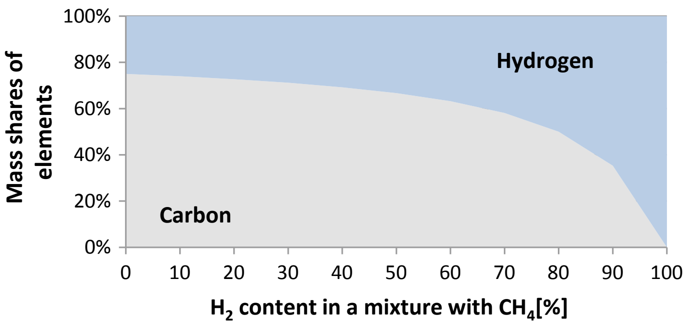


Fig. 12 Mass fraction of elements *c* and *h* in the methane-hydrogen fuel blend

= 16, H_2 = 2:

$$M_F = 16 \cdot (1 - z) + 2 \cdot z \quad \left[\frac{\text{kg}}{\text{kmol}}\right] \tag{2.1}$$

where:

z the proportion of hydrogen in the fuel blend.

The mass proportions of the elements *c* and *h* were calculated from the formulas:

$$c = \frac{12 \cdot (1 - z)}{M_F} \quad \left[\frac{\text{kg C}}{\text{kg pal}}\right] \tag{2.2}$$

$$h = \frac{4 \cdot (1 - z) + 2 \cdot z}{M_F} \quad \left[\frac{\text{kg H}}{\text{kg pal}}\right] \tag{2.3}$$

The calorific value of the methane-hydrogen blend was calculated based on the shares of the components, assuming their calorific values: 50.05 MJ/kg—methane and 122.5 MJ/kg—hydrogen [6, 35, 36]. The calorific value of CNG is slightly lower than for pure methane, because natural gas contains a certain amount of impurities in the form of heavier hydrocarbons, CO_2 and N_2. The values of the characteristic parameters are given in Table 2.

The values of the parameters characterizing the stoichiometric fuel-air mixture, taking into account the influence of the proportion of fuel components, are presented in table (Table 3), and the dependence of W_u on the amount of hydrogen addition to the fuel on the graph (Fig. 13).

The amount of chemical energy portion carried by the fresh load delivered to the air-fuel mixture, produced on the basis of a blend of methane and hydrogen, mixed in various proportions, is characterized not only by a variable calorific value, but also by a different density. Due to the volumetric filling of the cylinder, this is reflected in the mass of the fresh load:

Table 2 Characteristic parameters of tested fuels

CH_4/H_2 proportion	W_d (MJ/kg)	L_a (kgA/kgF)	ρ (kg/Nm^3)
100/0 (vol%)	50.050	17.482	0.717
95/5	50.430	17.596	0.685
90/10	50.910	17.720	0.653
85/15	51.435	17.860	0.622
80/20	52.016	18.010	0.590
70/30	53.388	18.370	0.526
60/40	55.137	18.826	0.463
50/50	57.442	19.424	0.400
CNG	49.93	17.48	0.717
Petrol	46.09	14.90	749.6

Table 3 Effect of addition of hydrogen to the fuel mixture parameters (λ = 1)

CH_4/H_2 proportion	M_u (kg/kmol)	M_B (kg/kmol)	R_u (J/kg K)	W_u (MJ/kg)
100/0 (vol%)	27.533	27.436	301.97	2.705
95/5	27.416	27.394	303.25	2.712
90/10	27.291	27.358	304.64	2.719
85/15	27.156	27.306	306.16	2.727
80/20	27.011	27.260	307.80	2.736
70/30	26.682	27.136	311.59	2.756
60/40	26.292	26.976	316.22	2.781
50/ 50	25.822	26.806	321.98	2.812

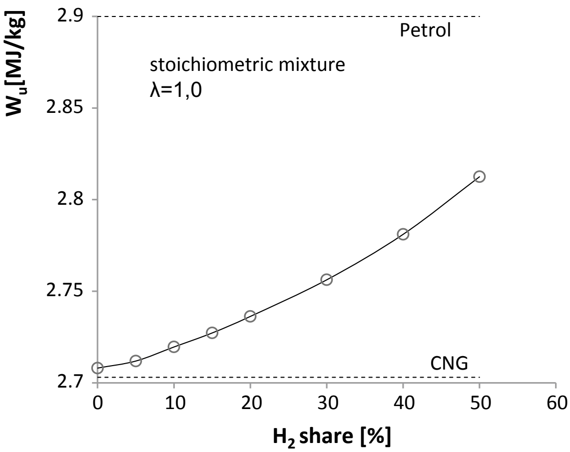


Fig. 13 Calorific value of the stoichiometric mixture depending on the share of hydrogen in the fuel blend

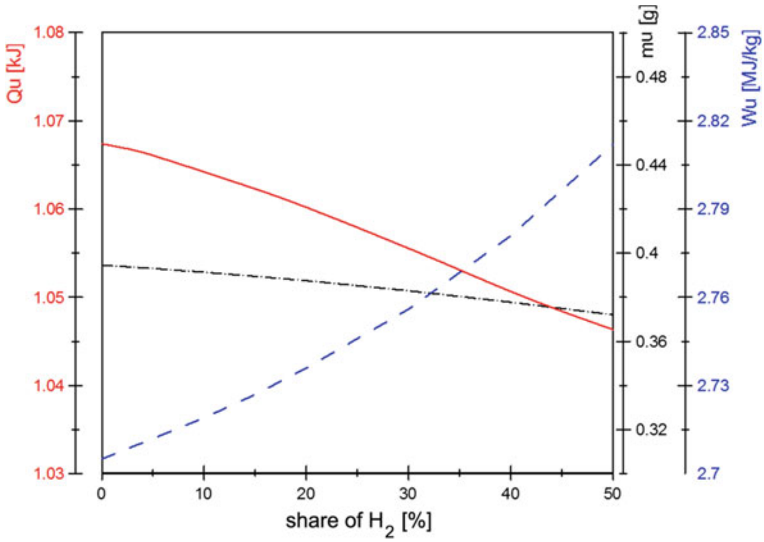


Fig. 14 Characteristic parameters of a fresh load depending on the H_2 content in the fuel, at a constant volumetric efficiency value, $\eta_v = 0.72$

$$m_u = m_f + \lambda \cdot m_a, \tag{2.4}$$

where:

m_f mass of fuel dose per cycle / cylinder,
m_a mass of air per cycle/cylinder.

Using the air demand L_a, the above relationship can be written as:

$$m_u = m_f(1 + \lambda \cdot L_a). \tag{2.5}$$

The process of filling the cylinder depends on the physical properties of the mixture, and on the structural parameters of the intake system, which determine the conditions in which the flow of load flows. The efficiency of this process is interpreted by the volumetric efficiency η_v. In fact, the nature of the changes $\eta_v(n)$ is visible in the image of the developed torque curve $T_o(n)$ (Fig. 14).

2.5 The Use of Methane-Hydrogen Blend in the SI Engine

2.5.1 Impact of Fuel Composition on Engine Performance

The use of methane-hydrogen fuel blend is motivated by two factors. The first is a practical factor, where the addition of hydrogen introduced into methane is to act as an activator in the combustion process. The second argument is related to the possibility of a significant reduction in CO_2 emissions, which is due to the fact that the increase in the proportion of hydrogen in the fuel eliminates some of the carbon that is bound in the form of CO_2 in the combustion process. These two important arguments mean that despite the unfavorable effect of the increasing share of hydrogen on the amount of energy supplied with a portion of charge to the cylinder (p. 2.2), the proposed solution is technically justified [37–40].

The rest of the chapter presents examples of experimental research results. The tests were carried out on a 4-cylinder engine with a capacity of 1.6 dm^3, which was installed in a C-segment passenger car. The tests were carried out on a chassis dynamometer. The car was equipped with an alternative CNG injection system.

Measurements of $P_o(n)$ and $T_o(n)$ carried out on the chassis dynamometer allow the assessment of changes in the value of engine performance parameters caused by the change in the composition of the fuel blend [41–43]. The maximum values are summarized in a separate Table 4.

The measured maximum values initially show a decrease, with a small proportion of H_2, in relation to the values obtained for pure CH_4. Further increasing the H_2 addition results in a significant increase in the achieved values. The highest power ($P_{max} = 52.98$ kW) was obtained when supplying a fuel with $H_2 = 20\%$. With larger addition, P_{max} is achieved slightly, but systematically decreases.

The impact of the fuel blend composition on the maximum torque values achieved is almost identical to that of engine power. At low hydrogen enrichment, the T_{max} value decreases slightly, however, along with the increase in the share of hydrogen in the fuel, its increase was noted (Table 4). The highest value of $T_{max} = 122.5$ Nm was measured when fed with 85% CH_4/15% H_2. For fuels with H_2 content above 15%, T_{max} values are gradually decreasing.

Measurements of power on the vehicle wheels P_w confirmed the trends of the observed changes. The measurements were made at maximum engine load and set speeds. The results of these measurements are illustrated in the graph prepared with

Table 4 List of maximum points output power and torque from the engine performance diagram [73]

P_{max} (kW)	At rpm	Fuel	T_{max} (Nm)	At rpm
50.9	5030	100% CH_4	115.2	2710
50.6	5260	95% CH_4, 5% H_2	113.1	2680
51.7	5300	90% CH_4, 10% H_2	117.0	2730
52.2	5250	85% CH_4, 15% H_2	122.5	2790
53.0	5250	80% CH_4, 20% H_2	118.6	2880
52.6	5300	70% CH_4, 30% H_2	117.9	2650
51.7	5300	60% CH_4, 40% H_2	117.7	2620
51.1	5300	50% CH_4, 50% H_2	116.3	2570

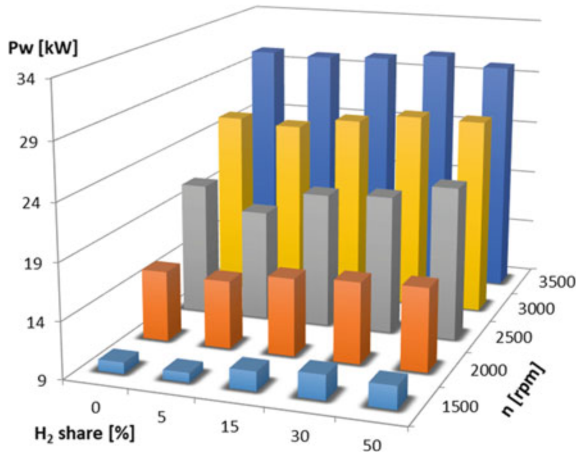


Fig. 15 Measured values power on wheel; WOT = 100%; λ = 1.0

the data table below (Fig. 15). It was found that for a 5% H_2 share, the P_w is lower in the entire range of the tested speed than in the case of methane supply.

2.5.2 Fuel Consumption and Total Efficiency

In order to assess the energy conversion efficiency of the tested engine, fuel consumption was also measured. Calculated G_h and measured simultaneously P_w, allowed calculation of ge in an engine fueled with blends of various proportions CH_4/H_2. The following formula was used:

$$g_e = \frac{G_h}{P_s} = \frac{G_h \cdot \eta_{mn}}{P_w}. \tag{2.6}$$

The obtained g_e results as a function of the hydrogen share in the fuel were presented in the form of a graph (Fig. 16) as a package of curves showing the g_e relationships for the determined speeds. The course of changes in the determined dependencies is similar. They show a downward trend in the whole area of the variable share of hydrogen. The decrease in the g_e value is dictated by both a decrease in the density of the fuel, which at the same volume (filling the cylinder) gives a smaller mass, as well as an overall increase in the generated power. The analysis of the calculated ηo shows a clear increase in overall efficiency, along with an increase in engine speed (Fig. 17). The tested engine obtained the highest efficiency when fed with a 50/50% blend.

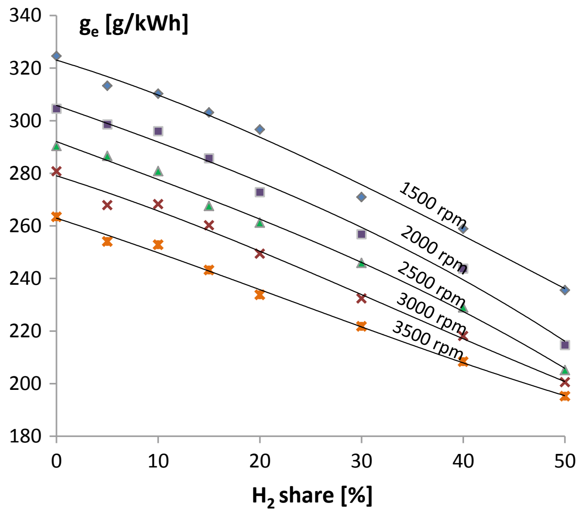


Fig. 16 Changes in specific fuel consumption depending on fuel composition and speed

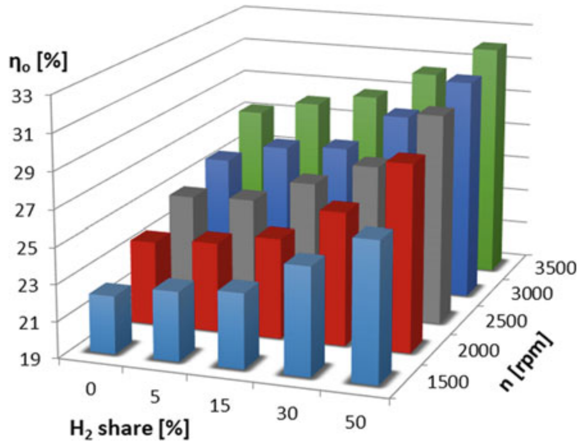


Fig. 17 Summary of the results of calculations η_o in the implemented scope of tests; full load; $\lambda = 1.0$

2.5.3 Impact of the Share of Hydrogen in Fuel on Thermodynamic Processes in the Engine

The enrichment of methane with hydrogen causes changes in two basic planes, which are visible in the observation of internal parameters illustrating the thermodynamic transformations of the working charge in the combustion chamber. In the course of indicated pressure, changes in the p_{max} value (Fig. 18) and pressure rise rate $dp/d\varphi$ (Fig. 19) are observed. The increasing share of hydrogen in fuel causes an increase in the combustion rate of the charge, increasing the dynamics of pressure increase. It also increases the p_{max} value. On the other hand, the presence of hydrogen adversely

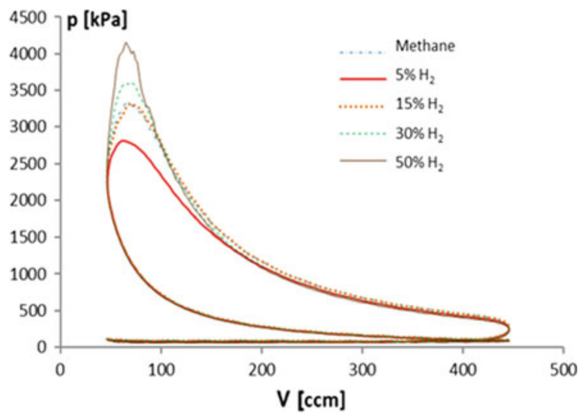


Fig. 18 Pressure changes in the *p*-*V* view in the tested engine fed with methane-hydrogen blends; $n = 2500$ rpm; full load; $\lambda = 1.0$

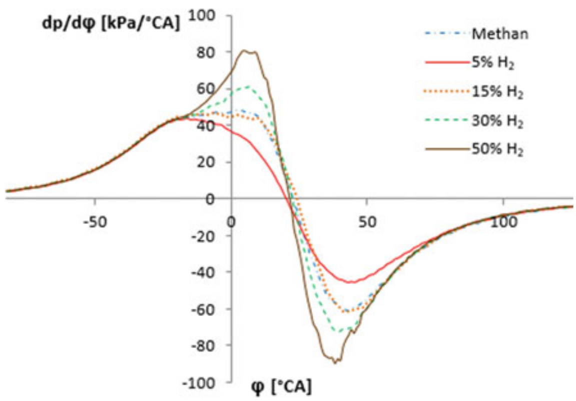


Fig. 19 Changes in the rate of pressure increase in the tested engine fed with methane-hydrogen blends; n $= 2500$ rpm; full load; $\lambda = 1.0$

affects the energy density of the charge. This means that while maintaining the stoichiometric composition, the proportion of air in the mixture produced increases.

The overlapping of these two opposing influences means that an effective pressure increase occurs with $H_2 > 15\%$. At smaller hydrogen proportions, a reduced pressure level was recorded in relation to the values obtained for the initial fuel, which was pure methane. Whereas the increasing H_2 share in the range of 15–50% maintains the upward trend of the values of indicated pressure. It is also worth noting that the change in fuel composition does not cause major displacements of the p_{max} occurrence point in the engine's work cycle. For the presented series of results this point occurs in the angle range CA $\varphi = 21$–$24°$ aTDC.

The directions of changes listed earlier are even more clearly visible in the observation of the course of energy release during combustion of a mixture with a variable share of hydrogen (Fig. 20). The increasing share of hydrogen causes an increase in the rate of heat release. This is evidenced by changes in the angle of inclination of the function in the middle of the graph, which corresponds to the phase of effective combustion (10% < MFB < 90%).

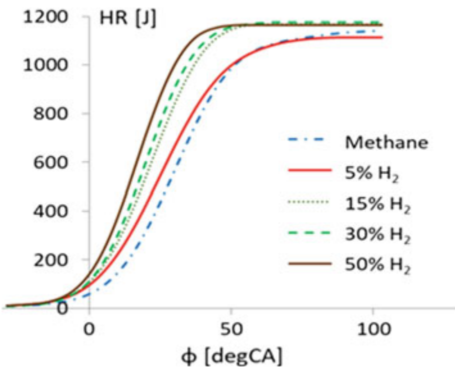


Fig. 20 Values of the function of heat dissipation in the combustion process in the tested engine fed by methane-hydrogen blends; n = 2500 rpm; full load; λ = 1.0

In the presented examples of results, however, the interpretation of transformations was only abandoned using the MFB parameter, because it could be unreliable, due to the comparison of mixtures with different calorific value W_u. The introduced relationship HR (φ) shows the amount of energy released taking into account this variable:

$$HR = MFB(\varphi) \cdot m_u \cdot W_u \quad [\text{J}]. \tag{2.7}$$

Another important conclusion concerns the changes in the amount of released energy in the combustion initiation phase, which is enhanced by observing the rate of heat release (Fig. 20). The addition of hydrogen to methane, from the smallest share, causes increased heat release rates. A further consequence of this change is the shortening of the combustion initiation phase, which confirms the adopted assumption about the activating interaction of additional hydrogen in the fuel blend with methane.

The process of burning a prepared portion of cargo requires a certain time. The rate at which this transformation occurs is characteristic of the specific fuel composition and the conditions prevailing in the combustion chamber. It is shaped by the physico-chemical parameters of the compounds involved in combustion (specificity of atomic bonds, unit activation energy, etc. …). In addition, there is also the influence of environmental parameters in which the reactions take place (pressure, temperature, etc. …). The total duration of combustion in the engine cylinder is shaped by the factors mentioned and the amount of charge delivered to the combustion chamber.

The duration of the individual stages of the combustion process when using methane-hydrogen blends shows a strong relationship between the amount of hydrogen in the fuel and the duration of these phases. Calculations made with the use of a mathematical model allowed to isolate the phase initiating the combustion process and the actual (effective) combustion phase.

Based on their analysis, it can be concluded that a particularly strong impact of the amount of hydrogen addition occurs in the initial phase, where charge combustion is initiated. As a consequence, the entire period (and time) that elapses from the

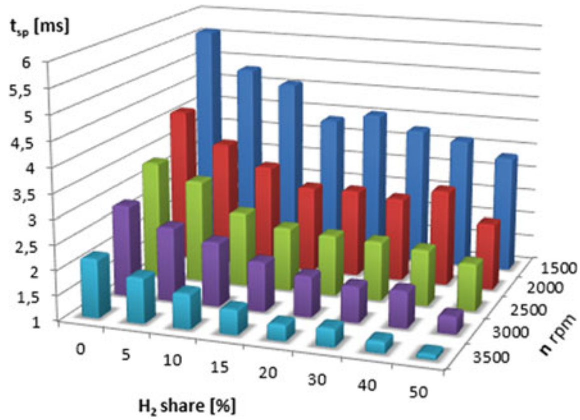


Fig. 21 Duration of the effective phase of the combustion process with variable hydrogen content in the fuel and selected rotational speeds; full load; λ = 1.0

moment of ignition to the end of the main combustion phase is shortened. The next graph (Fig. 21) presents the results of calculations of the effective combustion time determined in the tested states of operation of the engine operating at full load. These differences are so significant that with a mixture with the maximum tested share of $H_2 = 50\%$, the duration of effective combustion is reduced by half, compared to the results obtained when burning pure methane.

2.5.4 Analysis of the Exhaust Gas Temperature and Composition

The change in exhaust gas composition during the combustion process is strictly dependent on the combustion temperature $T_b(\varphi)$. Chemical reactions also occur after the flame has gone out. Carbon compounds undergo a process of dissociation, which involves a secondary "detachment" of the oxygen atom from the CO_2 molecule, which causes an increase in the proportion of CO at the expense of CO_2. The intensity of this process is associated with an increase in temperature, which weakens atomic bonds [44]. However, the increase in the number of free O atoms promotes the formation of NO.

For the above reasons, a parameter such as the temperature of the flue gas leaving the T_{ex} combustion chamber was distinguished in the study. In the case of the use of methane-hydrogen blends, the most important is the fact that generally there is a slight decrease in the T_{ex} value with an increasing share of hydrogen (Fig. 22). It can therefore be concluded that the use of the CH_4/H_2 blend as a fuel will not increase NO_x and CO emissions.

The basic composition of the emitted exhaust gas is strictly dependent on the composition of the fuel used. Figure 23 presents the content of the main exhaust components depending on the share of hydrogen in the fuel mixture. The most important change in this statement is a significant reduction in CO_2 emissions, which is the result of a reduced share of coal in the load prepared for combustion.

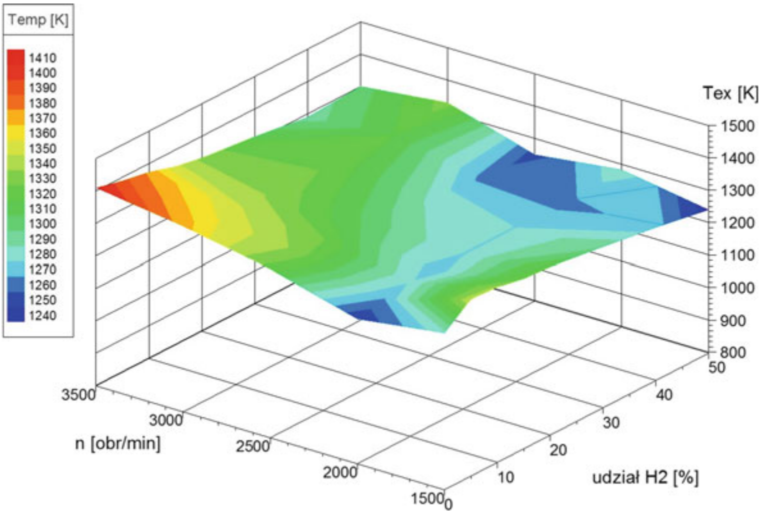


Fig. 22 Calculated temperature of the exhaust gas leaving the combustion chamber in the tested range of rotational speed and fuel composition changes; full load; $\lambda = 1.0$; EGR $= 0\%$

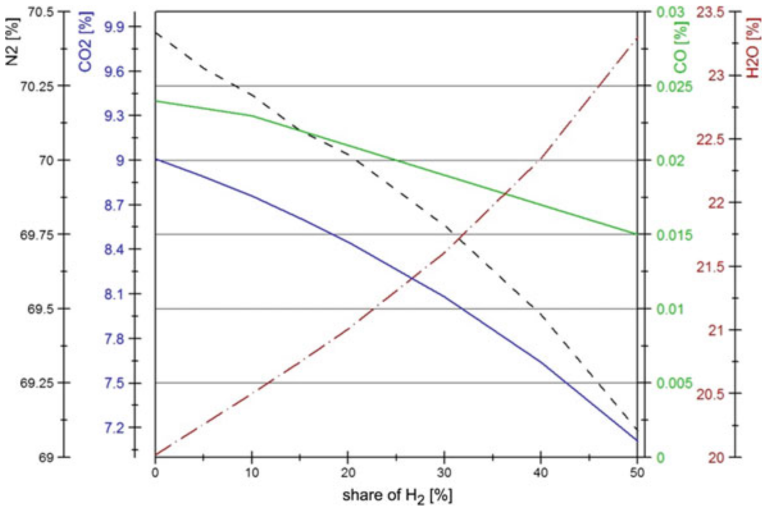


Fig. 23 Trends in changes of main exhaust components depending on the amount of H_2 to CH_4 addition, with stoichiometric combustion

With properly implemented combustion process (appropriate temperature, ignition conditions, composition of the mixture, etc. …) lower CO content can also be expected. The increase in the H_2O share in the exhaust gas is the result of an increased share of hydrogen in the fuel. These changes are also accompanied by a slight decrease in N_2 content in the emitted exhaust gases.

2.5.5 Limitation of Methane Enrichment with Hydrogen

The dynamics of the combustion process generated by the increased share of hydrogen causes greater pressure increases $dp/d\varphi$. This reveals an increase in the noise level and vibration emitted by the engine. In addition, the analysis of changes in $dp/d\varphi$ values carries information on the course of internal processes occurring in the tested engine. The sharp increase or irregularity in this course allows for the early detection of appearing detonation burn marks. Even when the phenomenon is not intense enough to be perceptible outside.

In the conducted tests, no external (sound of engine operation) signs of typical detonation combustion in the whole range of engine regulation and load were observed. But a detailed analysis of the recorded pressure signal in the range of changes in the maximum values of pressure increases achieved in subsequent working cycles, however, showed the appearance of birthmarks that suggest an early knocking phase. The occurrence of these ratings applies to the range corresponding to the full load engine operation and increased rotational speed ($n > 3000$ rpm) when supplied with blends with $H_2 > 30\%$.

Observing the distribution of maximum $dp/d\varphi$ values, determined for all tested fuel mixtures (Fig. 24), the results were divided into 3 zones (marked on the chart). In zone 1, dp_{max} points grouped in working cycles with a typical, smooth pressure pattern are grouped. The correctness of the course is achieved value and the occurrence of a point in the phase of pressure rise, before reaching p_{max} in a given working cycle.

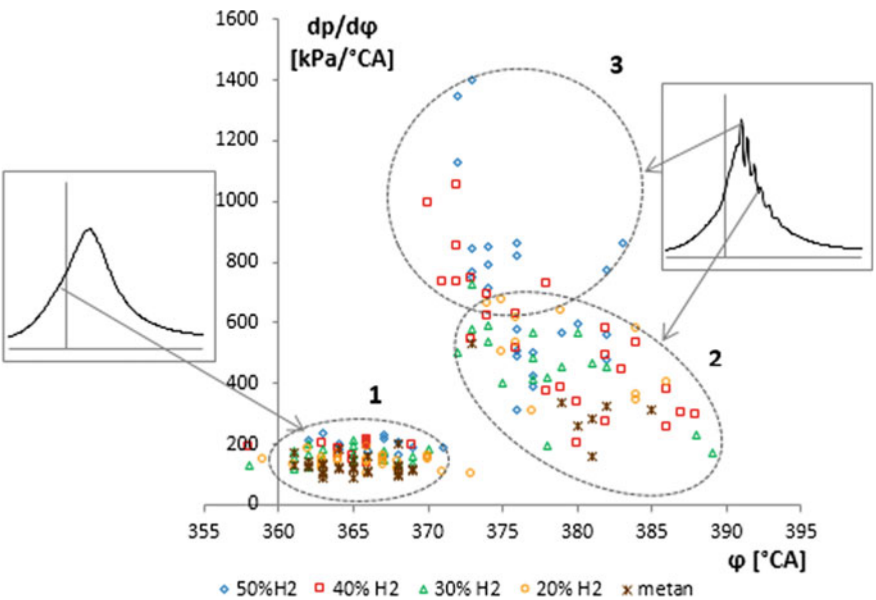


Fig. 24 Distribution of the occurrence of maximum increases $dp/d\varphi$ for various fuel blends; full load; $n = 3500$ rpm

In zones 2 and 3, work cycles are grouped in which the maximum pressure increase occurs after reaching p_{max}, i.e. in the zone where the pressure drops. This situation indicates the discontinuity of the pressure curve as a result of disturbances in the combustion process.

The difference between these groups is the value of dp_{max} in group 2, the pressure increases occurring do not exceed 600 kPa/ dCA and result from a change in the burning rate. This may be caused, e.g., by the heterogeneity of the burned charge. The last, third group is characterized by a higher pressure increase, $dp_{max} = 600$–1400 kPa/dCA. A characteristic feature of cycles in this group is the occurrence of dp_{max} around p_{max}. The reason for the occurrence of such pressure spikes may be a high detonation combustion. One possible justification for this fact is that such increases were only noted in the case of combustion of a blend with a significant proportion of hydrogen; $H_2 = 40$–50%.

The described phenomena appear at full engine load and increased rotational speed ($n > 3500$ rpm) and intensify with the increase of hydrogen content in the fuel. An illustration of the discussed issue is a graph showing the average values of dp_{max} (Fig. 25). The conclusion from the analysis of the phenomena observed is that an increase in the proportion of H_2 in fuel above 40% is undesirable due to the increase in the number of cycles with high dp_{max} values. Action in this direction is also ineffective due to the occurring power drop.

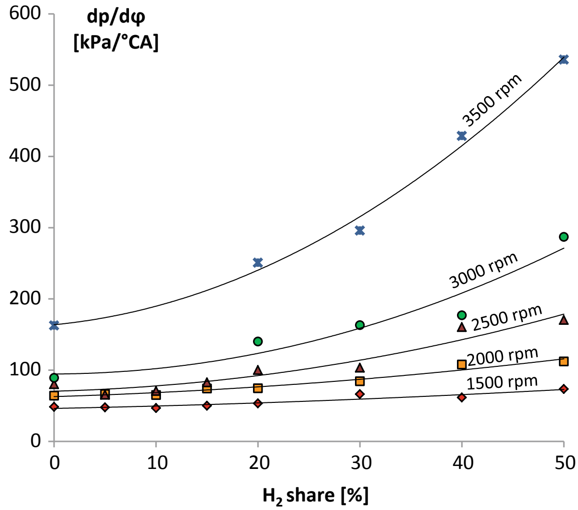


Fig. 25 Averaged, maximum values of $dp/d\varphi$ in recorded pressure runs for various fuels and speeds; full load; $\lambda = 1.0$; EGR = 0%

2.6 Comparison of Energy Conversion Efficiency in an Engine Powered by Low-Carbon Gas and Base Fuel

Measurements of power on the vehicle wheels—P_w, give the possibility of a direct comparison of the utility parameters of the vehicle using various fuels or regulatory settings. The changes in Pw that were observed with low-carbon gas fuels were referred to the value measured with the base fuel, i.e. 95 lead-free petrol (Fig. 26). Changes of P_w caused by the change of ignition advance angle when feeding CNG, initially cause an increase in the power value, and after exceeding the correction value of 9–10 dCA, the power begins to decrease. However, the effect of adding hydrogen to methane is different, where P_w growth was observed in the whole range of tested blends.

None of the solutions used could achieve the power generated when running on gasoline. The differences in the case of the ignition timing change were from 21 to 12% at the optimal ignition timing, and in the case of CH_4/H_2 blends the smallest decrease in power was 10% with a 50/50% ratio. In the scope of H_2 = 20–30% shares, the developed power on wheels is lower on average 15–17% than in the case of gasoline supply. The overall decrease in power is undoubtedly caused by a decrease in the energy potential of the charge in the combustion chamber—lower W_u.

Considering the general efficiency of the η_o engine, it can be seen that the nature of changes in its value, in both methods used to improve energy conversion (Fig. 27), is similar to changes in P_w. However, it should be noted that the achieved η_o equals, and in some cases, exceeds the values achieved with gasoline. This demonstrates the

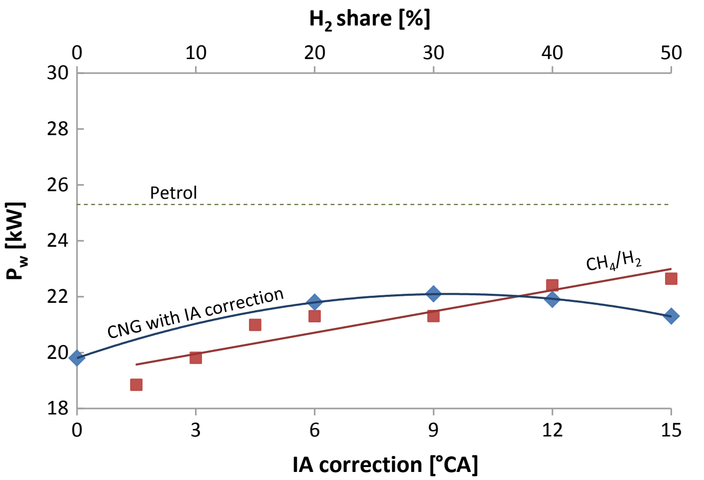


Fig. 26 Comparison of engine output power with feeding of petrol, CNG and CH_4/H_2; full load; λ = 1.0; n = 2500 rpm

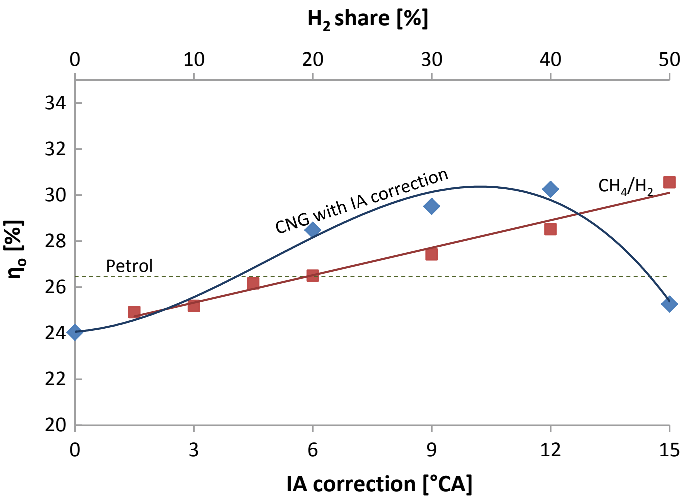


Fig. 27 Comparison of the overall efficiency of engine fed with a gasoline, CNG and CH_4/H_2 engine; full load; $\lambda = 1.0$; n = 2500 rpm

possibility of more efficient energy conversion in an SI engine when powered by low-carbon gaseous fuels.

The most important conclusion from this analysis is the real possibility of a significant reduction in CO_2 emissions (Table 5), using fuels with an increased proportion of hydrogen. This fact is one of the basic arguments justifying the need to develop applications of this type of fuel. The problem of CO_2 emissions as a greenhouse gas is currently recognized not only in the ecological dimension, but also gains importance in the economic and energy dimension, which is why every possibility of reducing its emissions is carefully analyzed.

Apart from the main components of exhaust gas, there is also a group of compounds with a relatively small proportion (less than 1% by volume), but essential in assessing the quality of the energy conversion system. It is primarily about the emission of toxic compounds such as: CO, NO_x and HC. Due to the reduced share

Table 5 Reduction of CO_2 concentration in exhaust gases for low-carbon fuels, $\lambda = 1.0$

Fuel	Emission level (%)
Petrol	100
CNG	71.7
90% CH_4 + 10% H_2	69.4
80% CH_4 + 20% H_2	67.1
70% CH_4 + 30% H_2	64.2
60% CH_4 + 40% H_2	60.2
50% CH_4 + 50% H_2	55.9

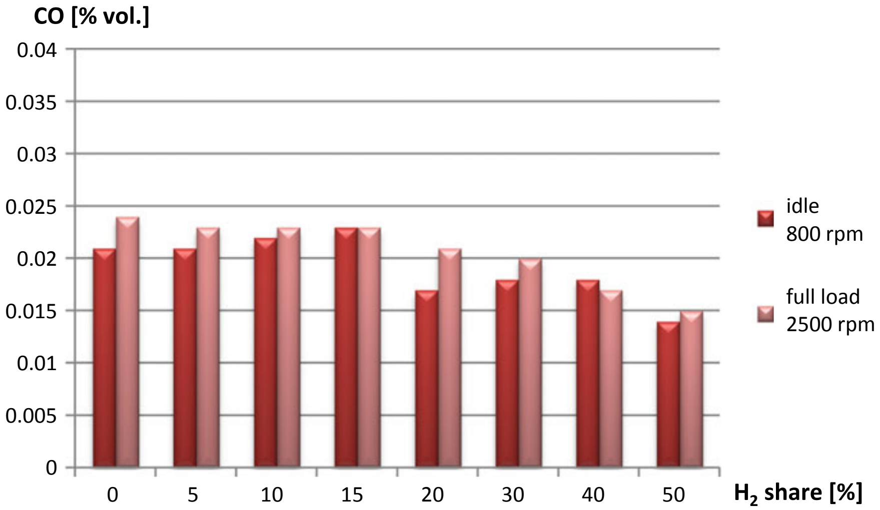


Fig. 28 CO concentration in exhaust gas upstream of the catalyst, at idle and at full load, with fuelling of CH_4/H_2; $\lambda = 1.0$; EGR = 0%

of carbon in fuel, there is also a decrease in CO emissions compared to the base fuel. The CO emissions shown in the diagrams (Fig. 28) contain the results obtained when the engine is idling and at full load. The decreasing share of carbon in the fuel makes it possible to obtain even lower CO content, which is confirmed by the results obtained when feeding with CH_4/H_2 blends.

The NO_x concentration when fueled with this type of fuel may be higher than in the case of gasoline combustion due to the occurrence of higher temperatures. This problem is a characteristic phenomenon in the combustion of stoichiometric charge based on low-carbon fuels and has been detailed in the conclusions of published tests performed in other institutions [20, 39, 45]. The increase in the share of hydrogen in the fuel did not cause clear changes in the NO content in the exhaust gas upstream of the catalyst (Fig. 29). At idle, it remained at a level of about 600 ppm, and at full load it was on average 800 ppm.

2.7 Directions for Further Development of Low Carbon Fuel Applications

The technical conditions of most modern IC engines in which gaseous fuels are burned are adapted and optimized for conventional liquid fuels [46, 47]. Evidence of this is the frequent identification of gaseous fuels as 'alternative fuels'. On the other hand, using existing solutions and adapting them to new power supply conditions is a great practical advantage and significantly speeds up technical development.

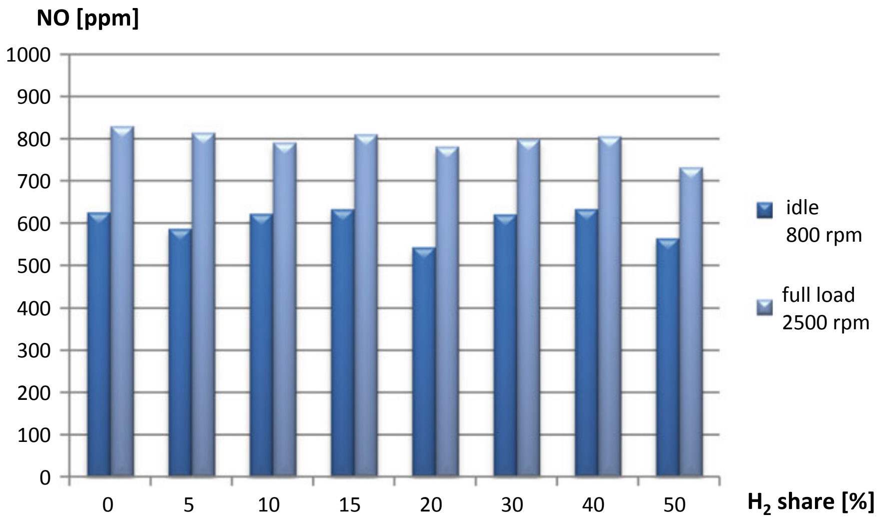


Fig. 29 NO concentration in the exhaust gas upstream of the catalyst, at idle and at full load, in an engine fuelled by CH_4/H_2; $\lambda = 1.0$; EGR = 0%

Therefore, in the conducted research it was adopted as one of the assumptions to use the existing CNG power installation in the power unit, for which the base fuel is gasoline.

The conducted analyzes draw attention to those engine design parameters that may be of great importance when changing fuel [48]. More detailed suggestions of issues resulting from these conclusions are presented in the diagram (Fig. 30). The first of the issues listed is the selection of construction materials. Their thermal conductivity was extracted as a parameter. It is important to prevent the increase of

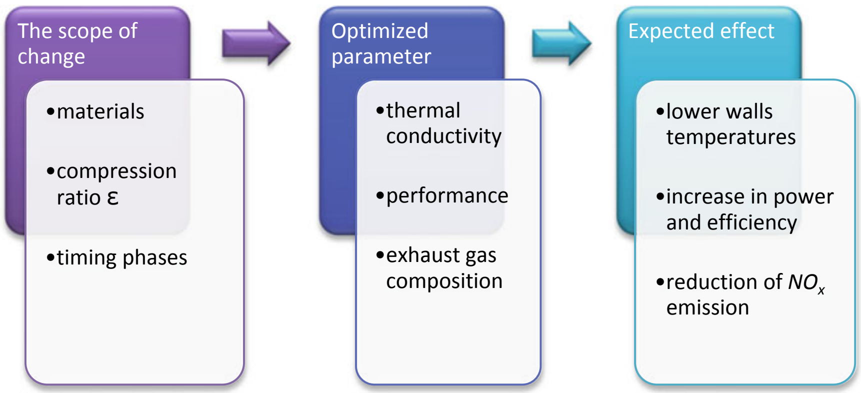


Fig. 30 Proposed improvement of engine design in the use of gaseous fuels

thermal stresses, which in the case of gas fuel supply may reach a high level with improper engine control. Another issue related to heat dissipation and cooling system operation is the use of heat energy in the gas fuel supply system. Design changes that take into account greater consolidation of these systems can prove very practical here.

The compression ratio ε is a parameter that determines, among others on the value of achieved pressure and its derivatives of performance parameters. The basic limitation of its value is fuel resistance to spontaneous ignition. Gaseous fuels generally have a higher octane number, so optimization ε seems justified in their case [49].

The development of gas fuel supply systems is a separate issue [50, 51]. In the field of fuel feeding and mixture production, the use of direct gas injection systems for the combustion chamber is a very interesting solution. The implementation of such a system requires the development of an appropriate injector design adapted to the specifics of the prevailing conditions and type of fuel. Another development aspect is the presence of hydrogen in the installation, which due to deep penetration requires the use of appropriate materials and special sealing techniques.

The last of the important issues are the ways of storing gaseous fuels on a vehicle. Here, too, with particular attention to the use of hydrogen. Whether in the form of a prepared mixture with methane, in pure form, or using the technology of producing this fuel directly on the vehicle. All these issues pose many challenges for scientists and engineers. Given the importance of a wide spectrum of benefits that can be achieved in this area, these works become even more interesting and valuable.

3 Hydrogen as a Fuel for H_2ICE and Fuel Cell

3.1 Some Relevant Properties of Hydrogen

Hydrogen is a fuel with unique physicochemical properties that distinguish it from conventional fuels. Its use to power internal combustion engines depends on effectively overcoming critical technical and economic barriers. Barriers that limit the widespread use of hydrogen as motor fuel are primarily associated with its production, storage, transport, and purity. Compared to other alternative fuels currently used, including natural gas, these barriers should be considered severe. The fundamental properties of hydrogen that are relevant to its employment as an engine fuel are listed in Table 1. These are compared to the corresponding values of methane, the other promising gaseous fuel for IC engine application and of petrol. Hydrogen heating value on a mass basis is the highest, but on volume, it is lowest.

The wide range of flammability limits, with flammable mixtures from as lean as $\lambda = 10$ to as reach as $\lambda = 0.13$ allows a wide range of engine power output through changes in mixture equivalence ratio. The flammability limits widen with increasing temperature, with the lower limit dropping to 2 vol% at 300 °C (equivalent to $\lambda = 20$).

The lower flammability limit increases with pressure, with the upper flammability limit having a fairy complex behaviour in terms of pressure dependence.

The high laminar flame speed clearly shows that thanks to hydrogen, extremely short burning speed with low efficiency can be achieved. Even with lean mixtures, the laminar combustion speed is much higher than with conventional fuels. However, in engines with hydrogen injection into the intake manifold when fed with stoichiometric mixtures, the engine load increases, and the rapid increase in pressure increases the noise. The minimum ignition energy of hydrogen-air mixtures at atmospheric condition is an order of magnitude lower than for methane-air mixtures and petrol-air mixtures. It is only 0.017 mJ, which is obtain for hydrogen concentration of 22–26% ($\lambda = 1.2$–1.5) [52]. The minimum ignition energy measured for capacitive spark discharge depend on the spark gap and for 2 mm gap is about 0.05 mJ more and less constant for hydrogen concentration between 10 and 50% ($\lambda = 0.42$–3.77) [53].

The lack of carbon makes hydrogen the only fuel that, at least in theory, allows the engine to be burned without emissions of carbon dioxide, carbon monoxide and hydrocarbons. During the actual engine operation, traces of these impurities may appear in the exhaust fumes, caused by the presence of lubricating oil in the combustion chamber, but the level is close to the detection limit. The only significant emission of nitrogen oxides during hydrogen exploitation should be given special attention.

Main unique features of hydrogen as a fuel for ICE are as follows [54]:

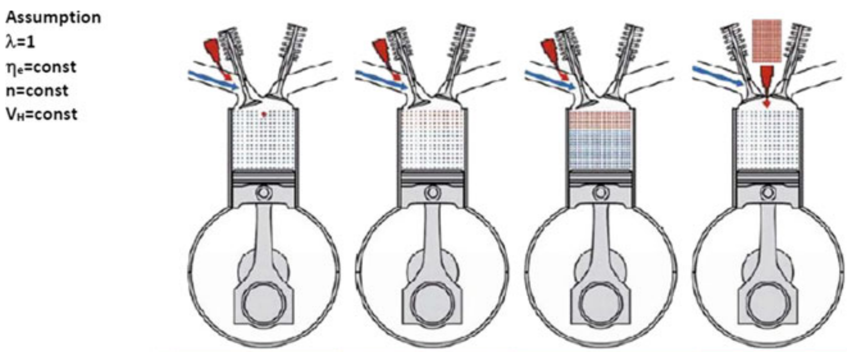
- hydrogen, over wide temperature and pressure ranges has very high flame propagation rates within the engine cylinder in comparison to other fuels.
- the lean operational limit mixture in a spark ignition engine when fuelled with hydrogen is very much lower than those for other common fuels,
- the operation on lean mixtures, in combination with the fast combustion energy release rates around top dead center associated with the very rapid burning of hydrogen–air mixtures results in high-output efficiency values,
- one of the most important features of hydrogen engine operation is that it is associated with less undesirable exhaust emissions than for operation on other fuels. As far as the contribution of the hydrogen fuel to emissions, there are no unburnt hydrocarbons, carbon monoxide, carbon dioxide, and oxides of sulfur, smoke or particulates,
- the fast burning characteristics of hydrogen permit much more satisfactory high-speed engine operation,
- varying the spark timing in hydrogen engine operation represents an unusually effective means for improving engine performance and avoidance of the incidence of knock,
- the sensitivity of the oxidation reactions of hydrogen to catalytic action with proper control can be made to serve positively towards enhancing engine performance.

In general, the presented above properties of hydrogen clearly show that it is extremely suitable as a fuel to drive an internal combustion engine. Different combustion concepts are possible, which differ significantly in terms of full load and complexity.

3.2 *Hydrogen as Fuel for Combustion Engine*

Preparation of the hydrogen and air mixture is carried out similarly like in engine fueled by conventional fuel. In Fig. 31. the influence of the mixture preparation method on its density in volume was discussed. The availability of suitable fuel is a key factor for H_2ICE. Conventional premixing using carburettor like equipment is limited by extremely low ignition energy required to the ignite the hydrogen-air mixture. To avoid and reduce the consequences of backfire or pre-ignition in the manifold fuel mixing should be done either directly upstream of the intake valve (Ported Fuel Injection—PFI or preferably inside the cylinder (Direct Injection—DI). Both methods require precise timing of fuel injection and thus fast injection valves providing good repeatability, sufficient flow area and high durability. Moreover, DI injectors have to withstand high temperatures and high combustion pressure.

Volumetric efficiency, fuel energy density and pre-ignition primarily determine the H_2ICE peak power output. The volumetric efficiency has been proved to be the



Fuel	Petrol	Hydrogen	Hydrogen cooled	Hydrogen
Mixture preparation	PFI	PFI	PFI	DI
Mixture temperature [K]	293	293	210	293
Mixture Heat Value [MJ/m³]	3.59	2.97	4.14	4.21
Power comparition [%]	100	83	115	117

Fig. 31 Hydrogen-air mixture density in volume depending on the method of its preparation. The density of dots corresponds to an increase in charge density. Blue dots correspond to air and red dots to fuel

limiting factor for determining the peak power output for most of the practical applications. For example, about 30% of hydrogen is possessed by mixture of hydrogen and air by volume, whereas a 2% gasoline is possessed by stoichiometric mixture of fully vaporized gasoline and air by volume. The higher energy content of hydrogen partially offsets the corresponding power density loss. The stoichiometric heat of combustion per standard kg of air is 3.37 and 2.83 MJ for hydrogen and gasoline, respectively. It follow that approximately 83% is the maximum power density of a pre-mixed or PFI-H_2CE, relative to the power density of the gasoline operated identical engine [55]. For applications where peak power output is limited by pre-ignition, H_2ICE power densities, relative to gasoline operation, can significantly be below 83%. For direct injection systems, which mix the fuel with the air after the intake valve closes (and thus the combustion chamber has 100% air), the maximum output of the engine can be approximately 15% higher than that for gasoline engines. Therefore, depending on how the fuel is metered, the maximum output for a hydrogen engine can be either 15% higher or 15% less than that of gasoline if a stoichiometric air/fuel ratio is used.

However, at a stoichiometric air/fuel ratio, the combustion temperature is very high and as a result it will form a large amount of nitrogen oxides (NO_x), which is a criteria pollutant. Since one of the reasons for using hydrogen is low exhaust emissions, therefore hydrogen engines are not normally designed to run at a stoichiometric air/fuel ratio. At this air/fuel ratio, the formation of NO_x is reduced to near zero. Unfortunately, this also reduces the power out-put. To make up the power loss, hydrogen engines are usually larger than gasoline engines, and/or are equipped with turbochargers or superchargers.

In addition to the method of the mixture preparation, essential factors that affect the combustion of hydrogen are also:

- hydrogen temperature, which may be equal to ambient temperature or lower (cryogenic),
- ignition initiation method, spark ignition or auto ignition,
- method of controlling the composition of the mixture, i.e., quantitative or qualitative regulation or combining both ways during charge preparation.

In the case of very varied and dynamic engine operation, the combination of the above functions is very desirable. Injecting cryogenic hydrogen into the intake manifold increases the density of the load, and thus the filling of the cylinder. Also, cooling the charge may limit the occurrence of phenomena interfering with the combustion process.

Depending on the type of ignition, a distinction is made between hydrogen, SI, CI, and HCCI engines. Due to the high auto-ignition temperature of hydrogen (about 585 °C), stable operation of the hydrogen-powered engine is only possible with high compression ratios and partial heating of the additional air. In current hydrogen engine applications, only the SI engines are used as the vehicle power source. Although in the past, many concepts have developed, and much research has been carried out on CI engines and hydrogen two-stroke engines, they are not used.

Currently, used methods of charge preparation in hydrogen engines are shown in Fig. 32. Figure 33 shows examples of two hydrogen engines, the first it is a 6-cylinder engine used by MAN to drive a bus, the second is a rotary engine developed by Mazda.

In the automotive industry, also BMW is currently a manufacturer that focuses on the development and commercialization of a hydrogen-powered internal combustion engine. BMW has cleverly developed a way that the engine can be powered by hydrogen or petrol on the road. This technology gives the user flexibility because the availability of hydrogen refueling stations around the world is still low.

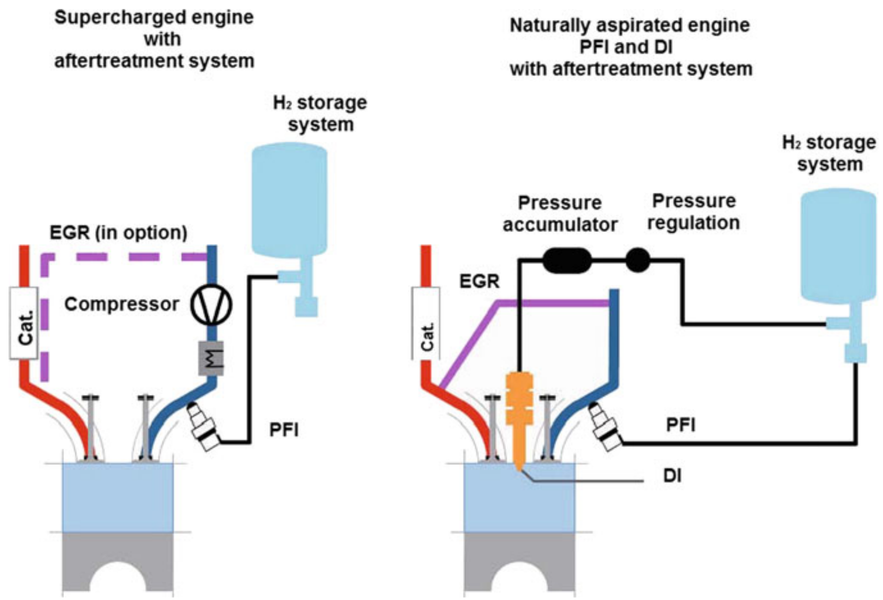


Fig. 32 Methods of preparation air-hydrogen mixture used in the practice

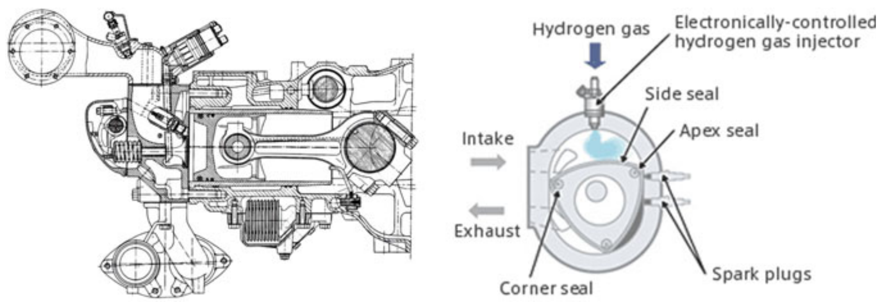


Fig. 33 Cross section of 12 L MAN hydrogen bus engine and the twin-rotor Wankel rotary be-fuel engine of Mazda RX-8, (configured to run on either hydrogen or gasoline)

Hydrogen as a fuel for internal combustion engines has many advantages in terms of flammability but requires careful consideration of the design of the engine to avoid abnormal combustion, which is a major problem in a hydrogen engine. As a result, this can improve engine performance, output power and reduce NO_x emissions.

3.3 Hydrogen as Fuel for Fuel Cell

3.3.1 Principle of Fuel Cell Operation

The fuel cell is an electrochemical device that generates electrical energy using chemical energy of the fuel. It takes fuel and air as input and supplies electricity and water as output through a chemical reaction [56]. Their characteristics are similar to a battery under load conditions. The basic principle was initially invented by Swiss scientist Christian Friedrich Schönbein in 1838, but the first fuel cell was only developed in 1839 by Sir William Robert Grove. The first usable and developed fuel cell was a 5 kW alkaline fuel cell, demonstrated by Sir Francis Bacon in 1950. Further improvement was done by International Fuel Cells, which developed an alkaline fuel cell with capacity of 12 kW for NASA's spacecraft. In mid-1960s, the researchers started working on fuel cells to avail them for general applications like stationary power supply and transportation. During these years, the governments of USA, Japan and Canada started funding the research works on fuel cell [16]. 50 years on, the research and development of fuel cell based application is still under progress and requires more concentration to reduce the expenses and improve the efficiency.

Fuel cells operate through electrochemical conversion process, which converts chemical energy into electrical energy. Input reactants (fuel and oxidant) are fed into a cell where the reaction occurs in the presence of an electrolyte, and electricity is generated as output. It is a zero-emission system because it does not emit any exhaust gas, and only produce water and heat. The schematic diagram of a simplified fuel cell is presented in Fig. 37. Different types of fuel cells take different types of fuel as input, but the chemical reaction that takes place in the fuel cell is similar. The reaction happens between oxygen from air and hydrogen from the fuel.

Leaving aside practical issues such as manufacturing and materials costs, the two fundamental technical problems with fuel cells are:

- the slow reaction rate, leading to low currents and power, and
- that hydrogen is not a readily available fuel.

To solve these problems, many different fuel cell types have been tried. The different fuel cell types are usually distinguished by the electrolyte that is used, though there are always other important differences as well. There is that six classes of fuel cell have emerged as viable systems for the present and near future. Basic information about these systems is given in Table 6.

In addition to facing different problems, the various fuel types also try to play to the strengths of fuel cells in different ways. The proton exchange membrane (PEM)

Table 6 Data for different types of fuel cell [74]

Fuel cell type	Mobile ion	Operating temperature	Application and notes
Alkaline AFC	OH^-	50–200 °C	Used in space vehicles, e.g. Apollo, Shuttle, Vehicles and mobile application and for lower power CHP systems
Proton exchange membrane PEMFC	H^+	30–100 °C	Vehicles and mobile application and for lower power CHP systems
Direct methanol DMFC	H^+	20–90 °C	Suitable for portable electronic systems of low power, running for long times
Phosphoric acid PAFC	H^+	~220 °C	Large numbers of 200 kW CHP systems in use
Molten carbonate MCFC	CO_3^{2-}	~650 °C	Suitable for medium- to large-scale CHP systems, up to MW capacity
Solid oxide SOFC	O^{2-}	500–1000 °C	Suitable for all size CHP systems, 2 kW to multi- MW

fuel cell capitalises on the essential simplicity of the fuel cell. The electrolyte is a solid polymer in which protons are mobile. The chemistry is the same as the acid electrolyte fuel cell of Fig. 34. With a solid and immobile electrolyte, this type of cell is inherently very simple.

PEMFCs are being used for a wide variety of applications, especially for power for fuel cell vehicles (FCVs). As a consequence of the high interest in FCVs and hydrogen, the development of PEMFC surpasses all other types of fuel cells. The PEMFC has a solid electrolyte which provides excellent resistance to gas crossover.

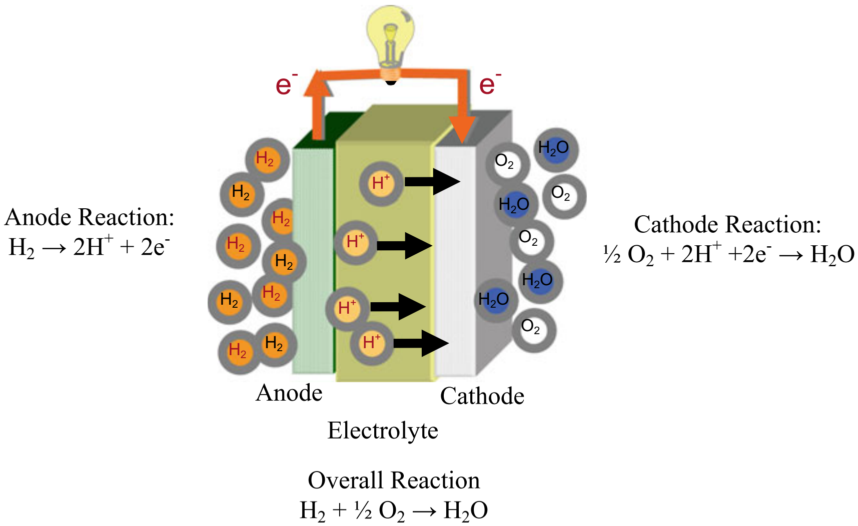


Fig. 34 Fuel cell diagram [65]

The PEFC's low operating temperature allows rapid start-up and, with the absence of corrosive cell constituents, the use of the exotic materials required in other fuel cell types, both in stack construction and in the BoP is not required. Test results have demonstrated that PEMFCs are capable of high current densities of over 2 kW/dm^3 and 2 W/cm^2. The PEMFC lends itself particularly to situations where pure hydrogen can be used as a fuel.

3.3.2 Fuel Cell Electric Vehicle (FCEV) and Fuel Cell Hybrid Electric Vehicle (FCHEV)

Fuel cell electric vehicles (FCEVs) use an all-electric powertrain but the energy source is a fuel cell stack. An FCEV is fueled with hydrogen, thus emits only water and heat. There is no tailpipe pollutant, thus it is recognized as zero emission vehicle. The fuel used in FCEV is either direct hydrogen which is stored in a tank mounted in the vehicle, or hydrogen extracted from fuel using a fuel processor. In Fig. 35, a typical powertrain configuration with optional fuel processor is shown [57]. The characteristic of FC is ideal for constant power supply, but not proper for abrupt change in power demand. Thus, slow speed vehicles such as forklifts, buses, trams, submarines, material handling vehicles are suitable for FC application. Nowadays, FC is being used for high speed vehicles as well. In order to produce high speed vehicles, different modifications can be made to the basic powertrain. Vehicle manufacturers like Honda, Toyota, and Hyundai are manufacturing high performance fuel cells for their vehicles.

The modification of FCEV powertrain leads to a new vehicle configuration called FCHEV. This type of vehicle architecture adopts another auxiliary ESS for supporting the fuel cell. Battery or ultracapacitor can be used as ESS as they can be charged and discharged based on the power demand and supply. Using fuel cell as the main energy source and battery or ultracapacitor as ESS in a hybrid vehicle, several issues

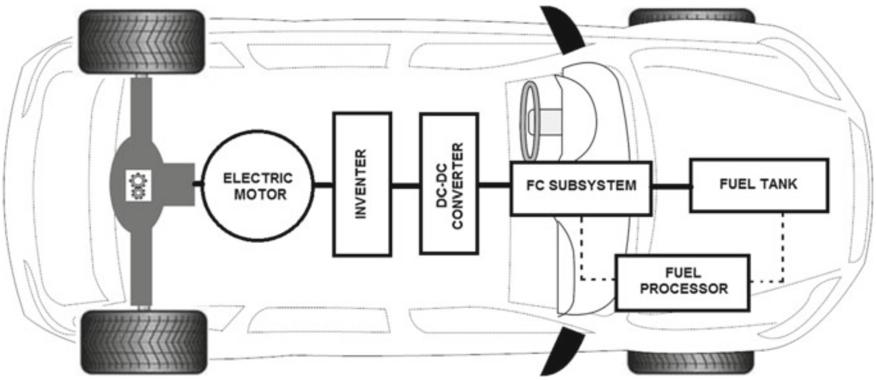


Fig. 35 Powertrain configuration of FCEV [58]

need to be taken care of to ensure efficient and smooth operation of the vehicle. Figure 36 shows a typical powertrain of FCHEV [58]. The possible issues are concerned with the power converter size, weight and reliability. Moreover, the converter efficiency, electromagnetic interference (EMI) and output voltage and current ripples are some important factors. The achievement in FCHEV research has led to successful commercial fuel cell vehicles. Table 7 shows some commercial and prototypes of fuel cell vehicles [58]. The table also shows the operating range of the vehicles in single fueling, and fuel economy in both city and highway driving conditions.

The energy sources for FCHEVs can be Fuel Cell (FC), Battery, Ultracapacitor (UC) and flywheel. The sources are chosen based on the basic power flow architecture, which is one source with high energy supply capability de-fined as "Main Energy Source" (MES), and another one with high power capability and reversibility facility which is known as "Rechargeable Energy Storage System" (RESS) [9]. Sometimes both sources have the reversibility and energy storage facility. MES is for

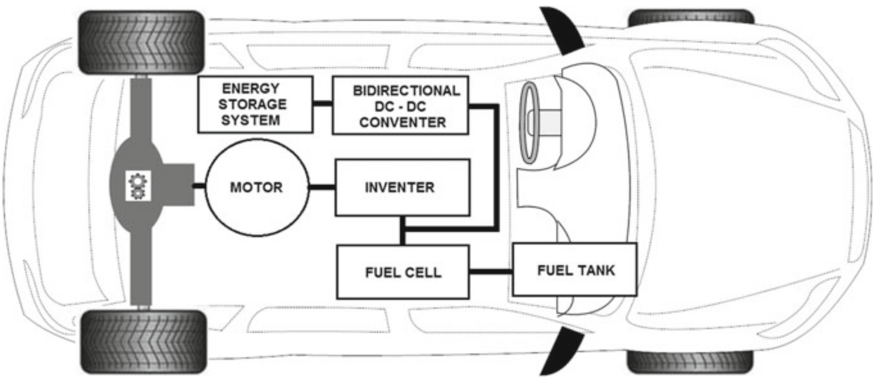


Fig. 36 Powertrain configuration of a FCHEV [58]

Table 7 Summary of different model of FCEVs and FCHEVs

Vehicle model	Type	Energy source	Range (km)
Honda FCX Clarity 2014	FCEV	Hydrogen	372
Honda Clarity Fuel Cell 2017	FCHEV	Hydrogen	698
Toyota Mirai 2016	FCEV	Hydrogen	500
Hyundai Tucson Fuel Cell 2016	FCEV	Hydrogen	426
Hyundai ix35 2013	FCHEV	Hydrogen	594
Toyota FCHV-adv	FCHEV	Hydrogen	643–804
Audi Sportback A7 H-tron Quattro 2014	FCHEV	Hydrogen	500
Honda FCV Concept 2014	FCEV	Hydrogen	700
Volkswagen Golf Hymotion 2014	FCEV	Hydrogen	498
Average mass of hydrogen in cylinders 5 kg			

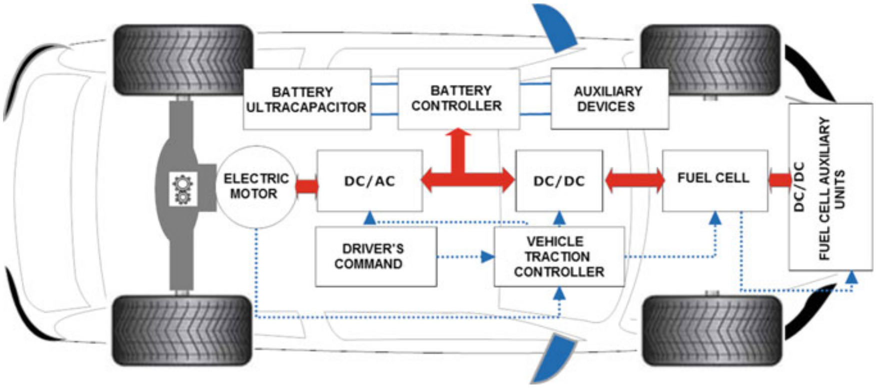


Fig. 37 Schematic of a fuel cell based power system for a passenger car [59]

steady state power supply and RESS is for transient power supply and regenerative braking usage. The RESS plays important role in the case of cold start of MES and sudden high-power demand such as in case of accelerating the vehicle. To decide the MES and RESS precisely, the knowledge of the power density and energy density is necessary.

A basic schematic diagram of a complete FC based HEV is shown in Fig. 37 [59]. In the system, fuel cell and battery are used as sources. The FC produces a low voltage, which is made usable by two DC/DC converters. One converter transfers power to the auxiliary loads such as water, fuel and air pumps, ventilation and control systems. Another converter transfers power to the input DC bus of traction motor inverter. The battery system is interfaced to the DC bus by a bidirectional converter. The traction motor inverter produces AC from the DC power supplied by FC and battery, and the traction motor uses the AC power to produce mechanical output used to drive the wheel of the vehicle. This system is a hybrid arrangement, which utilizes the regenerative braking power of the traction motor. The battery also works as power source during the initial startup of FC. Once the fuel cell is warmed up, the battery supply is turned off and the system runs by FC solely.

In the aforementioned topology ultracapacitor is not used; however, FCHEVs use various combinations of FC, UC and battery. Depending on the power conversion stages of fuel cell vehicle propulsion system, the configurations can be subcategorized into two types: multiple stage power conversion and single stage power conversion.

Several challenges such as technical, economical and others need to be subdued in order to make FCHEVs popular and successful competitor with conventional vehicles for users.

For vehicular application, Proton Exchange Membrane Fuel cells are ideal. To mitigate the basic commercial system packaging requirements, the power density and specific power targets of PEMFC have been achieved but further improvements are required. The anticipated specific power for automotive application is 1 kW/kg;

however, the achievement until year 2010 has only reached 0.65 kW/kg [34]. The catalyst used in PEMFC is platinum, which is an expensive and rare material. Due to this reason, the price of fuel cell is high. Performance and durability are other factors needed to be ensured. Hence, the volume, mass and cost of the stack needs to be reduced for commercial applications. The future challenges for FC system are the cost, performance, robust-ness and reliability.

3.4 Comparison of Vehicle Technologies

Hydrogen internal combustion engine (ICE) vehicles present much of the same promise as hydrogen fuel cell vehicles (FCVs): reduced reliance on imported oil and reduced carbon dioxide emissions. Proponents envision hydrogen ICE as a bridging technology from gasoline vehicles to hydrogen FCVs. The development of hydrogen ICE depends most on key uncertainties in the evolution of vehicle and production technology, the cost of crude oil, and the valuation of carbon dioxide emission reductions.

Much like hydrogen fuel cell vehicles, hydrogen ICE vehicles present a considerable promise: the chance to improve energy security and reduce carbon dioxide emissions by weaning of gasoline. And much like hydrogen FCVs, there are significant barriers to the adoption of hydrogen ICE vehicles, involving both technological improvements so it is competitive with gasoline-based alternatives as well as implementing a hydrogen fueling infrastructure. Looking beyond those similarities, distinctions quickly arise due to the nature of the hydrogen ICE technology that differentiate it from fuel cell and gasoline vehicles.

The most critical differences are the power produced by the engine, the fuel economy, the fuel tank size, and the state of development of the technology. Complicating any comparison is the vast uncertainty inherent in future vehicle technologies, hydrogen ICE included. If the fuel cell technology is developed to its potential, the fuel economy advantage it has over the hydrogen ICE technology appears to present a compelling case for FCVs in the long-term. This is particularly true because the higher fuel economy allows for a smaller fuel tank size for the same range, and fuel tank size is almost certain to be a key limitation for hydrogen vehicles.

However, the issue of power may prove to be a problem of FCVs, particularly for vehicles that need the capacity to perform at high loads, since adding more fuel cell stacks can add significantly to cost of the vehicle. Buses and trucks clearly fall into this category, and light duty vehicles such as light trucks and sport-utility vehicles may also fall into it, depending on the eventual cost of fuel cells.

In Fig. 38 provides a rough sketch of the relationship between engine efficiency and percent load for spark ignition engine (SI), compression-ignition engine (CI), and a single fuel cell (with equivalent output to these engine types).

Table 8 presents results of calculation made using the Advisor software. These results present of some of the most important characteristics of the four most relevant types of vehicles: gasoline ICE, gasoline hybrids, hydrogen ICE, and hydrogen FCVs.

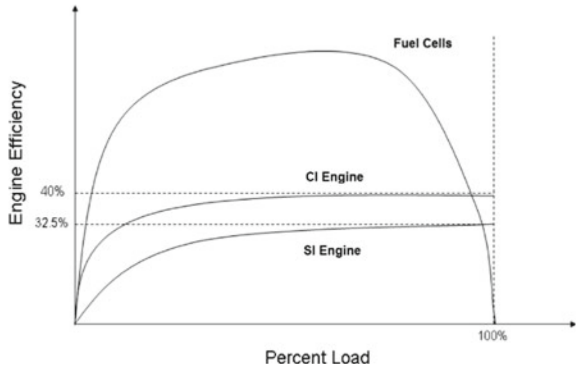


Fig. 38 Engine efficiency versus load for fuel cells, compression-ignition, and spark-ignition engines

Table 8 Comparison of different vehicle types

	Petrol ICE	Gasoline hybrid	H_2ICE	H_2 Fuel Cell
Engine type	Spark-ignition	Spark-ignition and motor	Spark ignition	Fuel cell and motor
Average engine efficiency (%)	~30	~30	~40	~55
Max engine efficiency (%)	32.5	32.5	~40	~65
Transmission type	Standard	CVT/hybrid	CVT/likely hybrid	CVT/likely hybrid
Transmission efficiency (%)	~40	~60	~60	~60
Fuel economy dm^3/100 km	11.2	7.59	5.74	4.61

The calculations were carried out for a car with a mass of 1400 kg, powered by a 55-kW engine in the urban and extra-urban cycle.

Spark-ignition engines have a maximum efficiency of 32.5% under normal conditions and at low loads have a much lower efficiency than this. Note that the additional electric engine in gasoline hybrid vehicles is highly efficient at very low percent loads, and is primarily used at low load levels, so gasoline hybrids do not suffer from this loss in efficiency at low loads as much. Compression-ignition engines tend to have a maximum efficiency rough in the range of 40%, and quickly reach efficiency levels close to the maximum efficiency at low percent loads.

The greater maximum engine efficiency is in large part the reason why diesel vehicles have better fuel economy than conventional vehicles.

A typical fuel cell stack can reach much higher efficiencies than either spark-ignition and CI engines, but it is important to note that as the fuel cell stack reaches maximum load, the efficiency drops precipitously, in contrast to the other engine types. The exact shape of this curve, and any quantitative estimates of fuel cell

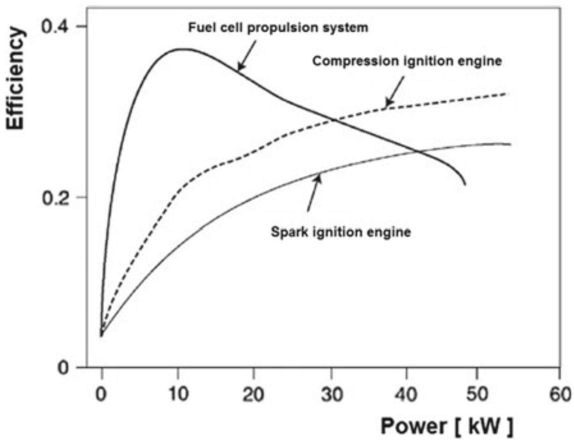


Fig. 39 Comparisons of power train efficiency of combustion engines and fuel cell systems (for a car with mass 1400 kg)

efficiency are highly speculative due to the many recent developments in fuel cell technology, but the general shape is robust (Fig. 39).

4 DME as a Fuel for IC Engines

DME (dimethyl ether) is a gas received from the application of physicochemical processes. Therefore, DME is not a natural substance but is of synthetic origin, received from the dehydration of methanol or by direct synthesis of syngas.

DME is now becoming an increasingly attractive energy carrier and in some circles is called the fuel of the future or the fuel of the twenty-first century. Excellent physicochemical properties and good storage conditions make DME highly suitable for use in industry and transport. The industrial use of DME boils down to its use as propellant gas in aerosols, while in transport it is used as fuel.

DME as a diesel fuel appeared in the world in 1999. At that time, the most important advantages of DME and the scope of its application were presented to the public. For the first time, DME was used as fuel in Japan, although it was used as a small amount of heating fuel in the 1980s in Ukraine and China, replacing local LPG shortages. In the 1980s, a gasoline or natural gas production program was established in Japan. During the processing of these minerals, DME was generated as waste at one stage. Currently, this technology is used as the basic way of obtaining DME, which is increasingly being replaced in the chemical industry by methanol.

Direct DME production began in the world in the 90 s. The largest DME producers are Japan, the United States and now also China and Iran. In these countries, DME is used as an energy carrier added to LPG, as a fuel for driving heavy transport and gas turbines. Currently, DME acquisition is carried out primarily through syngas processing. The following sections briefly describe the methods of syngas processing.

There are many sources of syngas. Syngas can be obtained from:

- extracted natural gas,
- coke oven gas,
- hard coal,
- biomass,
- plastic waste.

4.1 Received Syngas from Biomass

Current climate change, obtaining energy to sustain the global economy it is a key challenge. Climate change has been confirmed by a variety of scientific centers, which is why humanity faces the huge challenge of finding alternative energy sources. One way to obtain energy is to use biomass.

Plants generate carbohydrates from water and carbon dioxide captured from the atmosphere during photosynthesis using sunlight processes. This chemical energy of carbohydrates is a source of biomass energy. Organic plant resources are called biomass and the energy derived from them is called bioenergy.

The most important feature of bioenergy from, an environmental point of view is, its carbon footprint indifference. This means that bioenergy produced from biomass will not introduce into the environment an excess gas allowance contributing to global warming. Even the consumption of fuel generated from bioenergy releases the carbon dioxide accumulated in the plant growth processes used for biomass production. This causes the total carbon dioxide balance to be zero.

Zero excess carbon dioxide emission in the production of bioenergy is also the reason why it is possible to obtain fuels and chemicals represented by DME.

Table 9 shows the classification of biomass as different sources of bioenergy. The presented biomass was divided into two categories: biomass as a product (vegetation energy) and biomass from waste. Biomass as a product is primarily vegetation intended for energy purposes. As an example, the cultivation of sugar beet in Brazil, which is then used to produce methanol used to power motor vehicles.

Table 9 Biomass classification

Classification		Biomass resources examples
Plant biomass	Land	Sugar beets, corn, rape, etc.
	Underwater	Marine vegetation, microorganisms etc.
Biomass from waste	Agriculture	Rice straw, straw, sugarcane residue
	Forestry	Wood waste, sawmill waste, demolition waste
	Fishing	Fish processing residues, etc.
	Municipal waste	Excrement, meat residue, etc.
	Household waste	Garbage, sewage sludge etc.

The world resources of dry biomass were determined 1.2–2.4 trillion tons, this corresponds to the equivalent of 24–48 × 1021 J energy. Annually, around 1300 billion tonnes of dry biomass is produced worldwide, equivalent to 2580 trillion J per year. It is seven or eight times more than the world's energy needs. If biomass production were maintained at a higher level than its consumption, then sustainable bioenergy production would be achieved.

Since there are many sources of biomass extraction on the market today, a wide range of processes to obtain bioenergy has been developed. Biomass conversion is possible due to thermochemical or biochemical processes.

Thermochemical conversion is based on biomass combustion, thermal cracking and obtaining fuels, e.g. bio-diesel, in the esterification processes. Further technological processing of the obtained biofuel gives the opportunity to obtain and produce DME.

Thermochemical technology through gasification of biomass requires the use of air, steam and oxygen as gasifying agents and a mixture of hydrogen and carbon monoxide. The biggest challenge is the right selection of process parameters so as to get the least amount of pitch. Currently, there are over 200 technologies available which differ in pressure and temperature in the reactor, gasification agents and furnace type.

Table 10 presents the classification of gasification, containing various examples of processes carried out at atmospheric and elevated pressure as well as for different types of furnace bed and the furnace itself.

Obtaining of DME through biochemical conversion is very similar to typical fermentation allowing to obtain methanol and ethanol. Methane fermentation is possible to obtain through the use of municipal, domestic and agricultural waste. Fermentation is possible through the use of methane bacteria in an anaerobic environment, which allows the extraction of alcohols, acids, carbon dioxide and hydrogen. Methane fermentation can be carried out as a wet process where the reactions take place in the presence of water or dry fermentation in the absence of water. Dry fermentation is considered more efficient because the process reduces the weight and volume

Table 10 Gasification classification

Classification	Process condition
Gasification pressure	Normal pressure (0.1–0.12 MPa), increased pressure (0.5–2.5 MPa)
Gasification temperature	Low temperature process (700 °C or lower), high temperature process (700 °C or higher)
Gasification agents	Air, oxygen, carbon dioxide
Heating method	Direct gasification (part of the cartridge reacts with air to produce heat) Indirect gasification (raw material, gasification agents heated outside of the gasifier)
Type of gasification furnace	With a straight and fluidized bed, with a flow bed, a movable bed, two-column, etc.

of waste. Hence, this type of process is used in many projects. Fermentation with municipal and housing waste is particularly often used in Europe.

The biomass gasification process begins with heating to obtain gas components (CO, H_2, CH_4, H_2O), tar and hydrocarbons. The heating temperature is in the range of 200–600 °C and takes place in an anaerobic environment. The feed conversion is then about 75–90% as gas and 10–25% as tar. The gasification process at this stage can be regulated by the heating temperature, heating rate or pressure in the gasifier. The second step involves burning the components obtained in the previous stage in the presence of oxygen or air. At the same time, the combustion process is carried out with oxygen deficiency (coefficient 0.45), which causes the formation of incomplete combustion.

The third step is tar gasification. Most tar is gasified to carbon monoxide and hydrogen in the temperature range of 700–1200 °C. The Boudouard reaction is then used:

$$C + CO \rightarrow 2CO$$

And the reaction of water gas:

$$C + H_2O \rightarrow H_2 + CO$$

The gas obtained thanks to the above process consists of CO, H_2, CO_2, H_2O, CH_4, C_2 (or heavier) and N_2 (if air is used for gasification). The tar obtained during the gasification process is a burden and causes a number of problems because it settles on the walls of the reactor and condenses during the cooling of the obtained biogas. Figure 40 shows three types of gasifier.

The products formed in the gasification process also become the reason for the inertia of the reaction. The problem especially concerns products containing sulfur, nitrogen and methane compounds. Delaying the reaction is also a significant difficulty in maintaining a stable reaction during which DME is obtained. The amounts of methane obtained in the biomass gasification process can also be used to obtain DME, but due to gas contamination with sulfur compounds it is necessary to remove it first. The purification of methane obtained during biomass reforming is uneconomical from the point of obtaining DME.

Particular attention should be paid to biomass obtained from wood waste. At present, biomass from wood waste has enormous potential, which should be supported by centers financing waste management and enabling the acquisition of alternative fuels. One way to obtain DME is to use black liquor from wood processing in the paper industry. Installations of this type are already used in Sweden.

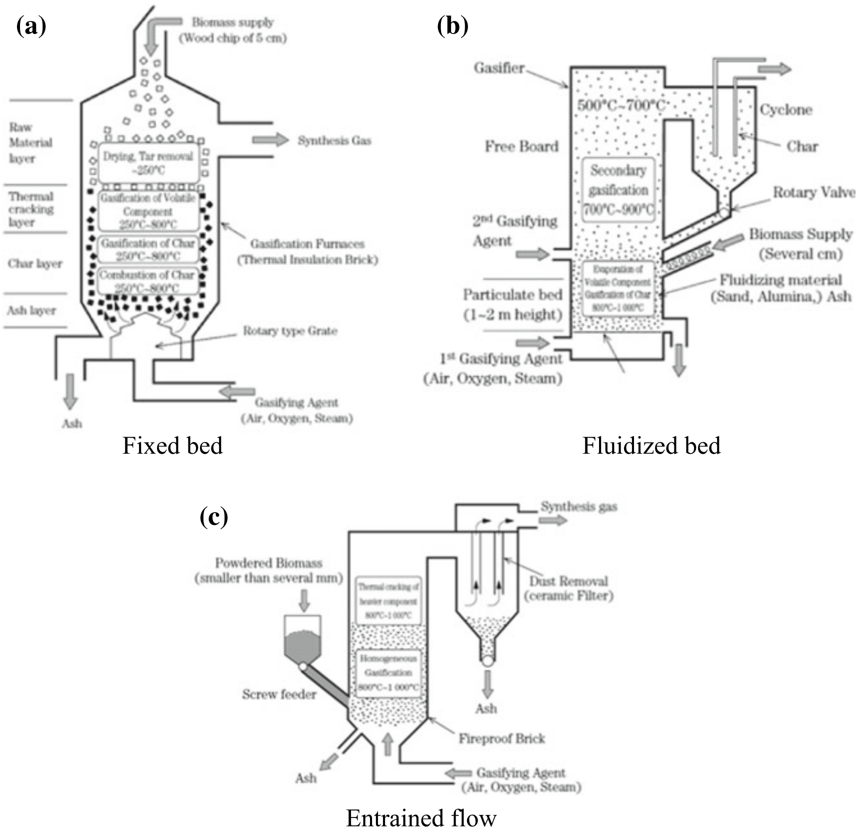


Fig. 40 Kind of biomass gasificator [66]

4.2 *Syngas from Plastic Waste*

The current global production of plastic waste reaches 10 million tons per year. Over 40% of plastic waste is collected at landfills, where it is uselessly stored. Incineration of plastic waste leads to the formation of poisonous substances, the best examples of which are dioxins. A certain limitation in waste utilization is their diversity, however, one should mention the high calorific value of plastic waste, similar to fossil fuel.

In recent years, a two-stage gasification of plastic waste has been developed, thanks to which it is possible to obtain syngas. The proposed waste utilization process solves the problem with heavy metals and dioxins resulting from incineration. This process is a form of waste incineration and obtaining base materials for the needs of the chemical industry. An exemplary diagram of the waste gasification process is presented in Fig. 41.

In the preparatory section of the system, the waste is ground and pressed using high pressure nitrogen. The preparatory activities carried out in this way will allow

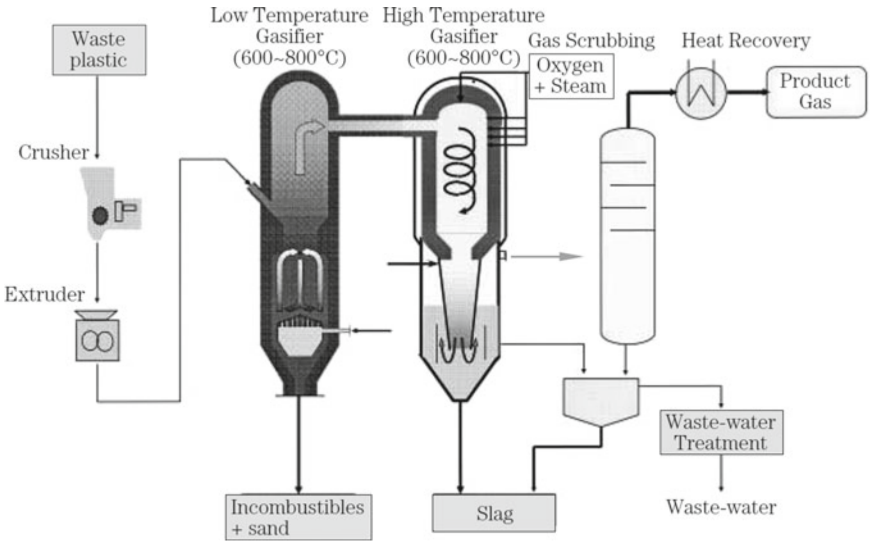


Fig. 41 Two way waste gasification scheme [66]

for obtaining an increased bulk density and allow the introduction of prepared waste to the first stage of the gasifier. The first stage is a low-temperature stage (600–800 °C) using a fluidized bed gasifier. Its design allows for lower collection of metal and non-flammable residues. Plastic waste is thermally decomposed and partly oxidized by oxygen, steam and gasification agents. The gasification components are fed through a fluidized bed at a lower temperature, resulting in gas, tar, slag containing H_2, CO, CO_2 and various hydrocarbons. Residues, like the aforementioned non-flammable components, are removed from the gasifier through a movable, vibrating screen. After removing small iron contents, waste gasifier products are returned to the process, i.e. re-introduced to gasification.

A high-temperature gasifier section is connected directly to the low-temperature gasifier. The high temperature gasifier consists of two connected chambers, upper chamber and combustion chamber. This device operates at temperatures in the range of 1300–1500 °C and pressures of 0.8–1.2 MPa. The gas is produced in the upper chamber. As in the case of the low-temperature gasifier, the gas is produced in the high-temperature gasifier using oxygen, steam and gasification agents.

Pyrolysis gas is produced in a low-temperature gasifier and fed into a high-temperature gasifier where syngas is produced at high temperature, which contains H_2, CO, CO_2 and various hydrocarbons. Hot syngas is directed to a water cooler where the temperature is lowered to 200 °C.

The indisputable advantage of the presented process is the possibility of processing unsorted plastic waste. Another advantage is the ability to recover non-ferrous metals (aluminum, copper, etc.) and iron in an anoxidized state. These materials are recovered from low temperature gasification residues. The process minimizes the use of solid fuels as hydrogen carriers necessary for the gasification process. Instead of these fuels, plastic waste is introduced, which ensures the possibility of gasification and thus limiting CO_2 emissions to the atmosphere.

4.3 Received and DME Synthesis

Currently, two methods of DME synthesis are used, the first is an indirect method where syngase is converted to methanol and then dehydrated to DME. The second method is the process of simultaneous synthesis and dehydration in the same reactor.

4.3.1 Indirect Process Synthesis

The methanol forming process of the indirect method is described by the following reaction:

$$CO + 2H_2 \rightarrow CH_3OH$$

In the presence of a copper catalyst, hydrogenation of carbon dioxide occurs in the first step:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

The copper catalyst shows high water and gas conversion activity:

$$CO + H_2O \rightarrow CO_2 + 2H_2$$

In the indirect method, methanol is dehydrated with the solid acid in DME in the second reaction step below:

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O$$

Dehydration is a simple exothermic reaction that allows its use in industry. The solid acid mentioned in the above reaction is usually clay or zeolite. An important issue is the strength of solid acid in the dehydration catalysis process. When the acidity is too high, when using zeolite, this leads to an increase in hydrocarbon emissions at low temperatures. High hydrocarbon emission leads to low efficiency of DME isolation.

Important advantages of the indirect process are the possibility of direct implementation of the process in industry. Existing methanol factories can therefore easily be converted to DME. This allows easy regulation of methanol and DME production.

4.3.2 Direct Process Reaction

The process of obtaining DME directly from syngas is carried out during the synthesis and dehydration of methanol simultaneously and additionally this process is carried out in one reactor. At the moment, there is no developed method for directly obtaining DME from syngas without forming methanol. The determined equilibrium of the DME composition is obtained at a temperature of 500–600 K and the ratio $H_2/CO =$ 1/1 or 2/1. Because during the exothermic reaction the number of molecules decreases to maintain high syngas conversion it is necessary to maintain high temperature and pressure of the process. Accordingly, one reaction is appropriate for this process:

$$3CO + 4H_2 \rightarrow DME + CO_2$$

Only when the ratio $H_2/CO = 2/1$ and the CO conversion is over 90%, the CO_2 efficiency decreases and the yield of DME and H2O increases. In this situation, the reaction can be saved as follows:

$$2CO + 4H_2 \rightarrow DME + H_2O$$

The equilibrium of CO conversion is higher when the synthesis of methanol and pure DME without H_2O can be obtained from an equilibrium point of view. This is the most important feature of the direct process.

4.3.3 Synthesis Reactors

As mentioned in previous subsections, there are currently two methods of obtaining direct and indirect DME. The reactions of both processes are also presented above. To obtain DME from both types of processes, it is necessary to use two different types of reactors. The basic reactor for the direct synthesis process is based on the reactor model used to obtain methanol in the Fischer-Trops process.

The basic design criteria for DME synthesis reactors are:

- control of heat transfer and obtaining the correct temperature profile,
- Improving reaction efficiency,
- Determination of the geometrical parameters of the reactor,
- Energy conversion.

Generally, DME synthesis reactors can be divided into two groups: fixed bed and other reactors (e.g. using a semi-liquid bed or moving bed).

4.4 DME Using for Combustion Engines

The increase in interest in methyl ether—DME, as an alternative fuel for motor vehicles, is mainly caused by the possibility of its production from many sources, such as natural gas, coal, biomass and black liquor, i.e. a semi-liquid, high-energy by-product in the cellulose industry. It is also possible to obtain DME as a product after processing plastic waste.

Currently used motor fuels are a mixture of hydrocarbons with a very wide boiling range. Table 6 presents a comparison of conventional and alternative fuels, which were classified taking into account their boiling point. Low-boiling fuels are methane and a mixture of petroleum gases, both currently used to power SI engines. Both of these gaseous fuels correspond to two others with a similar explosion limit, i.e. hydrogen and dimethyl ether (DME). DME has a boiling point corresponding to a mixture of petroleum gases, but its high cetane number allows it to be used to power CI engines.

Pollution of the environment with plastic waste is a global problem. The conversion of this waste into a useful substance is most desirable. Hence, it seems that the development of an efficient reactor installation allowing the processing of plastic waste or biomass into DME is a good way to solve this burning problem.

4.5 DME for CI Engines

Because DME is characterized by a very high cetane number, most of the currently ongoing development and implementation works include its use to power CI engines. The main problem is the development of reliable injection equipment to power the CI engine. Unlike diesel, DME does not have lubricating properties and hence problems arise with the durability and precision of the injection system.

DME injection equipment must ensure that the fuel is supplied to the combustion chamber in the liquid phase. At the same time, an important issue is how to control the amount of fuel entering the cylinder. Compliance with the above conditions is possible by using a fully digital control model analogous to currently used Common Rail systems (CR, common rail or battery system) (Table 11).

Such a system is equipped with a pressure accumulator in which fuel is stored under high pressure. High fuel pressure is obtained in a mechanically controlled high pressure pump. Electromagnetic injectors are responsible for feeding fuel to the combustion chamber. As mentioned earlier, a significant disadvantage of using DME is the lack of lubricating properties. In the systems of injector and high pressure pumps of the CR system, therefore, mating components may seize up. One of the ideas to solve this problem is the use of Teflon inserts (PTFE) or DLC (diamond-like-carbon) coatings, effectively reducing the friction forces between moving elements (Fig. 42).

Table 11 Comparison of physicochemical properties of selected fuels [66]

Parameter	Methan	Methanol	Dimethylo ether (DME)	Petrol	Diesel
Sign	CH_4	CH_3OH	CH_3OCH_3	C_7H_{16}	$C_{14}H_{30}$
Molecular weight (g/mol)	16.4	32.04	46.07	100.2	198.4
Density (g/cm^3)	0.720	0.792	0.661 (liquid) 2.057 (vapored)	0.737	0.856
Boiling temperature (°C)	−162	64	–24.9	17–220	140–380
Octane number	130	104	–	80–100	–
Cetane number	–	–	55–60	–	40–55
Low calorific value (MJ/kg)	50.2	20.1	28.8	43.47	41.66
Air/Fuel (kg/kg)	17.2	6.45	9.0	14.7	14.6
Ignition temperature (°C)	540–650	385	350	228–300	150–250
Burn velocity (cm/s)	30–33.8	52	42.9–61	30–60	
Coal (%)	74	37.5	52.2	85.5	87
Sulfur (ppm)	7–25	0	0	~200	~250

The solution to tribological problems in the injector and high pressure pump systems is partial feeding of the engine with diesel oil. The introduction of diesel fuel improves lubricating properties and reduces friction in moving parts. However, this solution reduces the ecological benefits of using DME fuel. An example of an injector adapted to supply DME is shown in Fig. 43.

DME is introduced into the combustion chamber in the evaporated phase under the same high pressure as in the case of diesel fuel. However, due to the physicochemical properties and, above all, the low boiling point (−25 °C), a higher speed of mixing DME with air is obtained and a more homogeneous fuel-air mixture is created. Changes in the rate of formation of the fuel-air mixture force changes in the DME injection parameter settings, which in turn also affects the emission of such an engine.

In the DME fuel supply system there is also a problem of the evaporated fuel phase. The fuel is fed to the engine in a liquid state, however, due to the physicochemical properties of DME, some of the fuel on its way to the injectors may be partially evaporated. Evaporated DME must be captured and liquefied again. In the case of CR DME systems, this role is performed by the compressor, which is an integral part

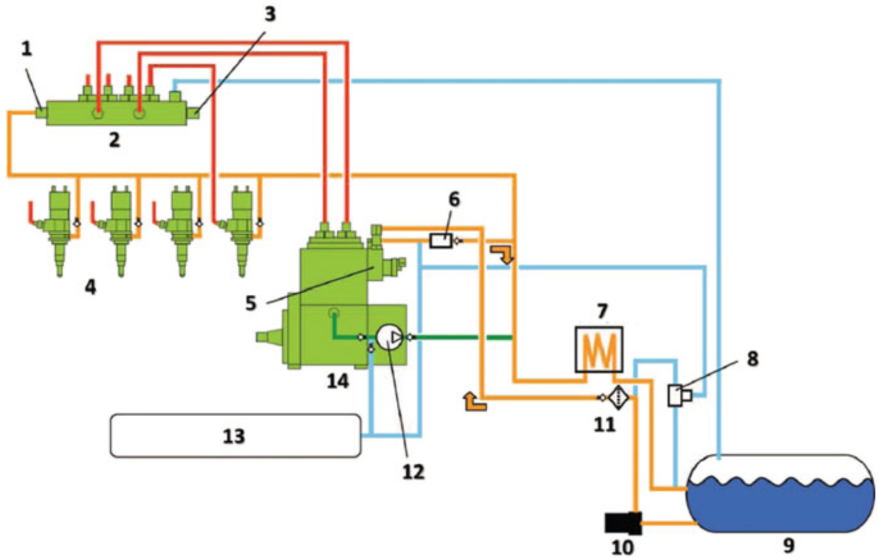


Fig. 42 Common Rail DME scheme [67]. where: 1—tank fuel pressure control valve, 2—pressure tank, 3—tank fuel pressure sensor, 4—injectors CR, 5—pressure regulator, 6—check valve, 7—heat exchanger, 8—three-way relief valve, 9—DME fuel tank, 10—pump with safety valve system, 11—DME fuel filter, 12—excess pressure fuel return compressor, 13—DME evaporated phase excess tank, 14—high pressure pump assembly

of the high pressure pump. This compressor raises the DME pressure to the liquefied state and releases the prepared fuels back to the tank but already in the liquid phase.

The European producer investigating the possibility of using DME for transport is Volvo. Volvo has proposed a group of trucks (GVW over 12 tones) powered by DME (Fig. 44).

Studies on the use of DME in public transport were also conducted in Moscow. Vehicles participating in the program have been minimally prepared to supply DME. The power supply system has been expanded with modules enabling the mixture of diesel and DME to be fed to the combustion chamber. The vehicles were equipped with a dual fuel storage system, a separate tank was DME and a separate tank was intended for diesel. The project was implemented with engines of 4000 cm^3 capacity, but no details were given regarding the output parameters of the engines.

The largest research projects on the use of DME are carried out in Japan, China and South Korea. Examples of vehicles powered by DME are shown in Fig. 45.

Projects carried out in Japan are designed not only to develop engine power supply systems but also to develop a full fuel distribution infrastructure. This is important in the process of placing new fuel on the market.

The undoubted advantage of using DME to power diesel engines is their smaller, negative impact on the natural environment. The reduction of negative environmental impact is partly due to the physicochemical properties of dimethyl ether. However,

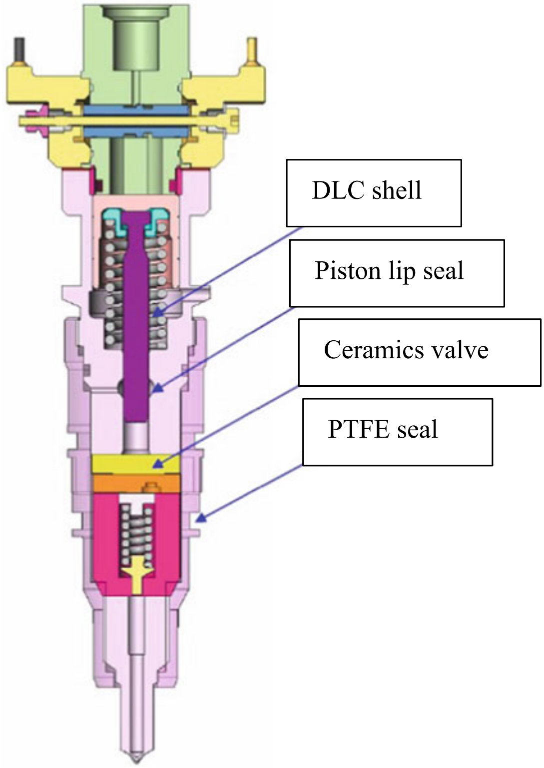


Fig. 43 SIEMENS injector cross section for DME use [68]

Fig. 44 Volvo FH12 heavy duty truck DME feeded [77]

Fig. 45 Examples of DME powered vehicles used in Japan and South Korea [66]

reduction of the environmental impact is only possible in certain ranges. Figures 46, 47 and 48 show examples of CO, HC and NO_x emissions for a diesel and diesel fueled vehicle (Diesel).

Analyzing the presented results, it is possible to determine that for low loads, almost for every fraction of emitted pollutants, this emission is much lower for DME compared to ON. However, in the case of higher loads, the tendency becomes the

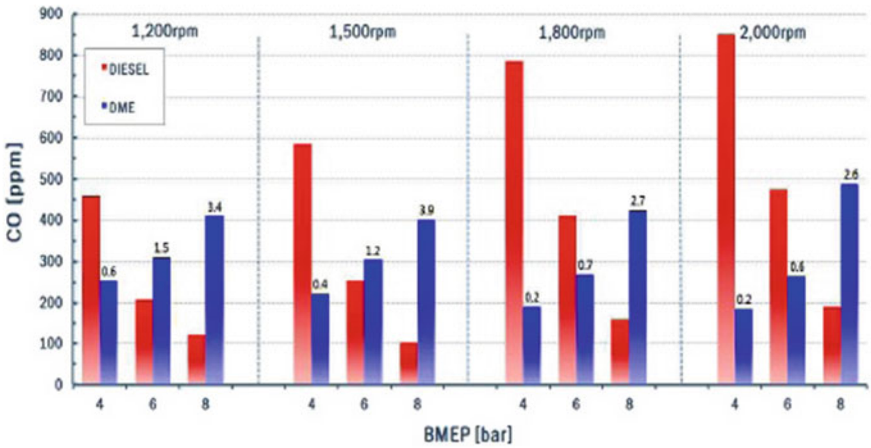


Fig. 46 CO emission for diesel and DME [69]

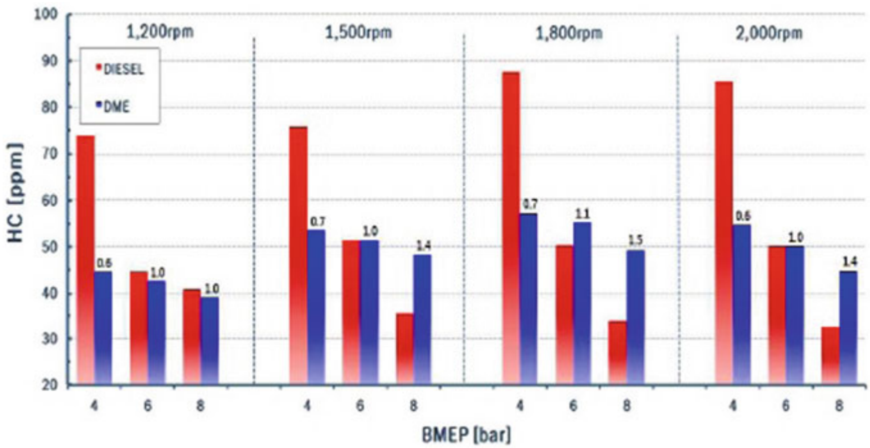


Fig. 47 HC emission for diesel and DME [69]

opposite. This is due to the need to develop new methods for reducing emissions of individual components.

The use of a catalyst in the exhaust system reduces emissions of almost all components (Fig. 49).

The change of fuel supplying CI engines to dimethyl ether also results in a reduction of noise emissions. Quick mixing of DME with air and greater tendency to self-ignition facilitate the initiation of the combustion process, which in turn reduces engine noise. An important advantage of DME is also the low harmfulness of the fuel itself when it enters the atmosphere. DME is not prone to enlarging the ozone hole and therefore also to global warming. This important factor should also consider the

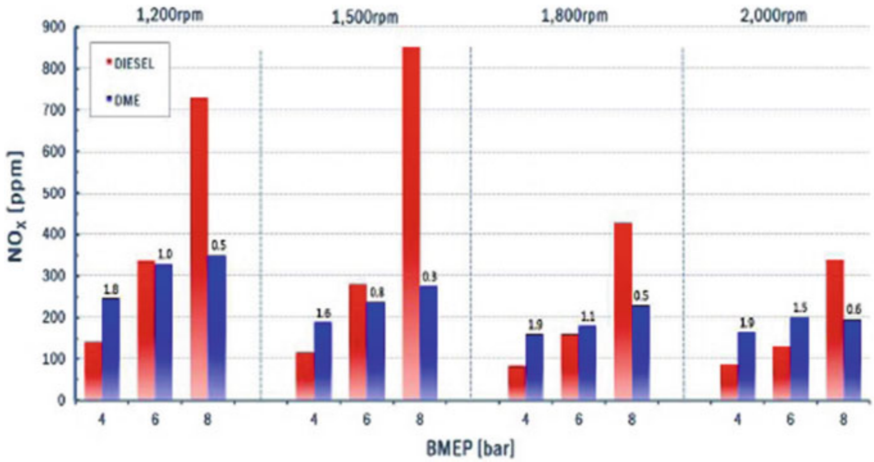


Fig. 48 NO_x emission for diesel and DME [69]

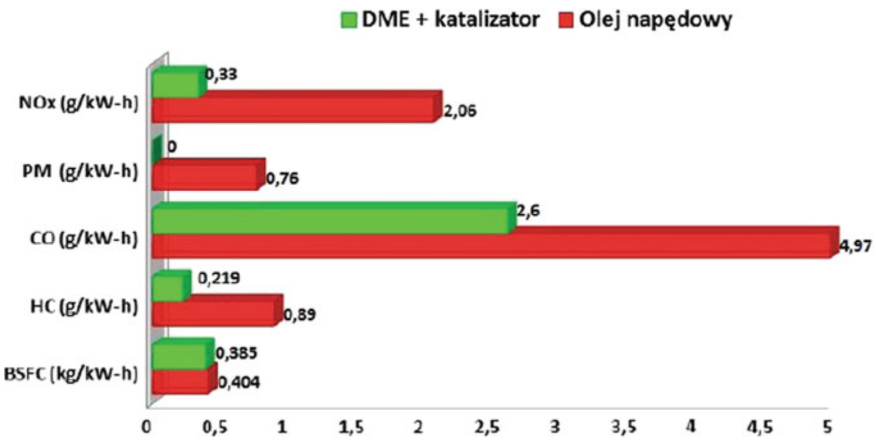


Fig. 49 Comparison of exhaust emissions for an ON and DME powered vehicle using a catalyst [70]

possibility of introducing DME as a full-fledged ecological fuel enabling the supply of CI engines.

4.6 SI Engines Feeded DME and LPG Mixtures

However, bearing in mind the fact that the physicochemical properties of DME are similar to LPG, DME is mixed with LPG and usually used as gas fuel for household appliances, as well as as fuel for gas engines driving generators and heat pumps. The possibility of mixing LPG and DME and its use as a supplement or instead of LPG will be conducive to both fuel diversification and increased energy security.

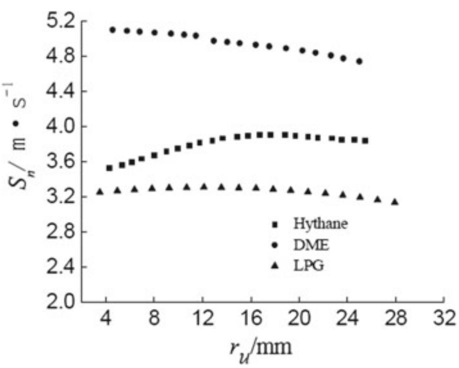
Because DME has a low octane value, it cannot be used to drive a SI motor without any additions. The easy mixing of LPG and DME was used during tests of the stationary SI engine, designed for the micro cogeneration system, propelled by LPG and DME mixtures with a DME mass share of 5–40% [71]. These studies allowed the development of combustion control algorithms, primarily in the field of detonation combustion control based on the signals of a standard detonation combustion sensor and ionization current control. It has also been shown that:

- it is possible to obtain the developed power for an engine powered solely by LPG,
- it is possible to start a cold engine without any modifications during its start when powered with mixtures containing 5–10% DME,
- ignition delay and changing the excess air coefficient enables the engine to operate without knocking when it is fed with a mixture of 30% DME,
- in the exhaust gases of the engine there is a high concentration of DME and formaldehyde, as well as NMHC hydrocarbons, significantly reduced downstream of the catalyst.

Similarly like hydrogen, DME is an activator of the combustion process. Higher hydrogen and DME combustion speeds accelerate the process of initiating the combustion of natural gas and LPG, which we now widely use to drive motor vehicles (Fig. 50).

In the case of SI engines that are fitted with motor vehicles, it is necessary to use apparatus adapted for the storage and distribution of DME. Due to similar properties of DME and LPG, it is therefore possible to use the existing apparatus of the LPG installation. The only necessary modification is changing the material used for the seals. In the case of DME, there is an intensive process of penetrating deep into plastic materials, which results in the phenomenon of increasing the volume of sealing elements. Increasing the volume may lead to dysfunction of the systems responsible for allowing fuel flow (solenoid valves).

Fig. 50 Comparison of engine emission for engine feeded LPG and DME [78]



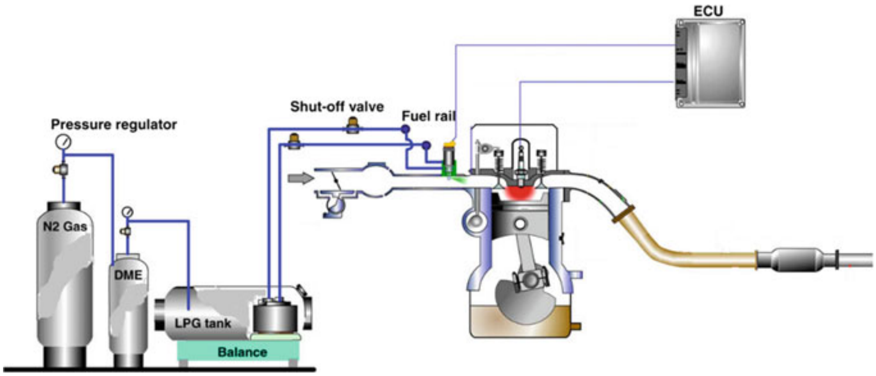


Fig. 51 LPG and DME mixtures stand scheme [71]

Due to the need to use DME as an LPG additive, the problem arises as to how to enrich LPG. DME additive applications can be carried out, e.g. at the LPG bottling plant stage, where it is possible to load the right amount of DME during loading or just before loading. It is also possible to make a mixing system, the initial installation of which was carried out at the Faculty of Transport and Aeronautical Engineering of the Silesian University of Technology. The installation diagram is shown in Fig. 51.

Using the apparatus presented, tests were carried out on the impact of DME admixtures on the dynamic parameters of the engine. Thanks to this research, it was possible to assess the efficiency of LPG and DME fuel mixture combustion.

4.7 LPG and DME Mixtures for Household Use

The world consumption of LPG is currently very high. China is the third largest country using around 16,200,000 tons of LPG (data from 2002). The LPG market in this country is growing by around 20% year on year. While the internal production of LPG begins to reach its maximum, growing consumption forces an increase in exports. Assuming that 50% of imported fuel will be replaced by DME, then it will be necessary to import over 3,000,000 tones of LPG. Thus, by estimating China's demand for fuel for domestic consumption, the increase in demand would be about 9.5–10 million tones of LPG, and the demand for DME would exceed 4–5 million tones. Currently, larger urban agglomerations in China use natural gas or coal gas for municipal purposes. The advantage of DME is ease of storage and transport, and a relatively high energy density, because DME is stored in a liquid state. Thus DME can be an excellent diversification for LPG. Compared to LPG, dimethyl ether has the following advantages:

- At the same temperature, the vapor pressure in the tank is much lower than LPG. DME is therefore safer for transport and storage,

Fig. 52 DME container for household use [79]

- In the volatile state, DME has a lower flammability limit, which makes it safer to use,
- DEM calorific value is lower, but it needs less oxygen to burn because it contains oxygen in itself,
- DME flame temperature is higher.

For cities with a gas network (e.g. natural gas), the change of fuel type is not very complicated. The only drawback of this implementation is the need to replace cutting valves due to other sealing materials, resistant to DME. As for cities and villages without a gas network, it is possible to organize individual or organized DME transport stored in classic cylindrical tanks used for LPG storage (Fig. 52).

DME was introduced as a substitute for LPG in several Chinese cities. These changes were positively received by the inhabitants.

Not only China plans to introduce a DME additive for LPG or even replace LPG with dimethyl ether. Also, in Iran, extensive work is being carried out allowing the introduction of an app. 20% for home use.

Brazil is another country where the diversification of LPG and heating oil is to take place. In Brazil, all heating oil and LPG are imported. The implemented works are to replace these fuels with DME produced in own, national reactor installations.

5 Conclusions

To sum up the whole issue, the following conclusions can be made:

1. The switch to hydrogen from fossil fuels offers many benefits, including energy security and lower carbon dioxide emissions if the hydrogen comes from renewable sources. However, such a transition is a change in the way we produce, distribute, and consume energy, and as a result, it cannot be underestimated. Also, other competing technologies may hamper the development of hydrogen as a viable transport fuel.
2. Modern hydrogen technologies used in motor vehicles provide fuel chemical energy conversion with efficiency close to 60%. However, they are too expensive and, as a consequence, the scope of their use is significantly limited.

3. Currently produced hydrogen-powered vehicles equipped with a fuel cell, chemical and electric energy storage unit and an electric motor are complicated in their construction. Despite the relatively good range, the possibility of their exploitation is limited by infrastructure (e.g., Hydrogen filling stations).
4. The use of mixtures of gaseous fuels and above all hydrogen and methane ensures a significant reduction of emissions and also the possibility for a smooth transition to hydrogen propulsion in the near future. In the case of hydrogen-methane mixtures, the ecological effect increases when one or both are made from renewable sources (i.e., they are a mixture of Bio-hydrogen and Bio-methane).
5. The application of CH_4/H_2 or HCNG blends is also one of the stages leading to the advancement of systems based on pure hydrogen as fuel. The fundamental motivator is a reduced emission of CO_2. Fuels of this type are characterized by an increased share of hydrogen energy compared to the energy generated by the oxidation of carbon.
6. The results of the conducted experimental and simulation research have shown that the low-carbon fuels selected for the tests can be used as full-value regular fuels in spark ignition engines. In addition, practical use of methane-hydrogen mixtures is possible using existing CNG systems.
7. DME can be easily pressurised and handled as a liquid. DME show promising features as fuel candidates with the Otto and the diesel engine and comparing with other fuels from an LCA point of view, these fuels show highest energy efficiency from "well-to-wheel".
8. DME and hydrogen had the highest efficiency, when analysed from "Well-to-Wheel". Hydrogen could be of great interest in the long-term future, but it is obvious that DME could be of great interest on a shorter timeframe.
9. As an alternative fuel, dimethyl ether can address energy security, energy conservation, environmental concerns, and the pragmatic realization of depleting petroleum reserves.
10. As fuel processors and fuel cells are introduced to the public, dimethyl ether can be further exploited as a non-toxic, non-corrosive, environmentally benign hydrogen carrier produced from domestic resources.

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Environmental Aspects of the Production and Use of Biofuels in Transport

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Abstract The article presents a comprehensive analysis of the environmental aspects of the production and use of biofuels in transport. It is stated that the environmental impact occurs at all stages of production and processing of bioenergy raw materials. It is substantial during land use change and production intensification, and minimal greenhouse gas emissions are observed when lignocellulosic fuels are used. Life cycle analysis shows that battery electric vehicles have a better greenhouse gas saving than most biofuels. At the same time, a large-scale implementation of renewable energy sources is needed to reduce harmful emissions from electricity generation. It is established that the use of carbon-neutral synthetic biofuels is a promising way to achieve the complete decarbonisation of the transport sector.

Keywords Biofuels · Greenhouse gases · Emissions · Life cycle analysis · Battery electric vehicle

1 Using of Biomass-Based Alternative Fuels in Automotive Industry

The existence of energy is a fundamental requirement for the development of all aspects of society. Energy is also needed to maintain the existence of ecosystems, life and human civilization. However, the use of fossil energy sources can cause

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a number of problems [1]. The energy from fossil fuels is non-renewable, and its overuse leads to a major energy crisis, which is now a major concern in the world. In this case, the demand for energy in transport grew faster than in most other economy sectors from 45 EJ in 1973 to 110 EJ in 2014 and increased its proportion in the total final consumption from 23 to 28% [2]. Due to the population growth, gross domestic product growth and rise in living standards, the demand for energy in the transport sector is expected to increase by about 40% by 2050 [3].

The use of conventional fossil fuels also contributes to the generation of pollutants that accelerate global warming, for example, the increase in carbon dioxide and other greenhouse gases [4–6]. According to different sources, the transport sector—road, air, and water transport—accounts for about 20% of the world's greenhouse gas emissions (Fig. 1) and is considered the most difficult sector for decarbonisation [7].

The development and operation of automobile transport are determined by two distinct and contradictory trends. On the one hand, the attained level of motorization reflects the technical and economic potential for social development and helps to meet the social needs of the population, and, on the other hand, it increases the negative environmental impact. That is, the improvement of transport vehicles to support human life and activities does not only improve people's transportation options, it also causes significant environmental pollution.

Studies on the socio-economic assessment of the effects of atmospheric pollution show that a significant proportion of the potential damage is attributable to the component related to the environmental impact on human health [10]. The analysis of the atmospheric pollution in cities with intense car traffic shows that nitrogen oxides (NO_x) and carcinogenic hydrocarbons have the most dangerous effect on human body. Their proportion in the assessment of the environmental hazard of automobile engines is 95%. Particularly dangerous are their derivatives, nitrocarcinogens,

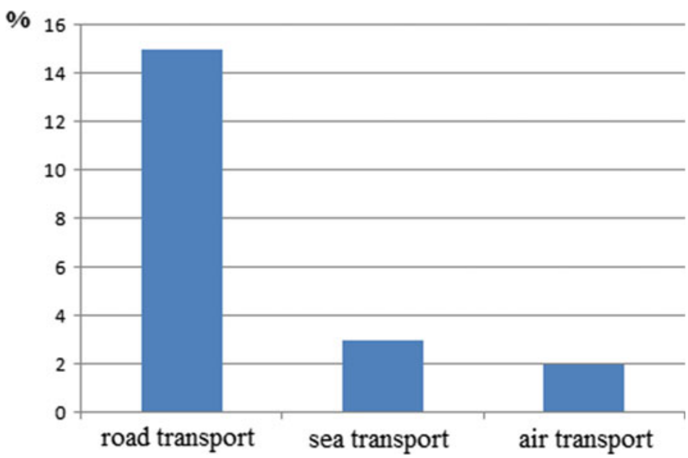


Fig. 1 Proportions of emissions from different modes of transport [8, 9]

which cause synergism and mutagenic properties. Some of the major carriers of carcinogens and nitrocarcinogens, which significantly enhance their aggressiveness, are carbon-based micro-fine solids [11].

However, unless cardinal measures are taken, the emissions will increase due to the growing demand for transport [12]. The total number of motor cars is expected to double by 2035 and reach 1.7 billion units [13]. The European Union is intended to reduce greenhouse gas emissions from transport by 60% by 2050, compared to 1990 [14].

Reducing greenhouse gas emissions and enhancing the energy security of states pose significant challenges for the transport sector in the coming decades.

Thus, at present, it is important to develop fuel technologies in road transport which would help to significantly improve the ecological and economic performance of vehicles using renewable alternative motor fuels.

It should be mentioned that modern systems based on fossil fuels provide a rather flexible energy supply for power plants, boilers and transport vehicles in liquid, gaseous and solid forms. Today's energy systems are based on infrastructure and storages and meet the needs by means of long-distance transportation of fossil fuels by ships and pipelines globally and to the national or regional energy infrastructures, for example, coal, gas and oil storages. Hence, the global system is based on the large-scale storage and transportation of energy-intensive fossil fuels, which can usually flexibly meet the requirements at the right time and place. Though the power system based on fossil fuels is a reality, the current challenge is to create an equivalent or more flexible energy supply system with an increase in the proportion of renewable energy.

Although biomass-based alternative fuels have significant potential for reducing pollutants in the long run, in our opinion, the technological potential for fossil-fuel vehicles should be used more efficiently to improve the environmental situation.

At the present stage of the automotive industry development the main indicators of internal combustion engines are considered to be the mileage rating and toxicity of exhaust gases.

The ways to improve the environmental safety of vehicle engines both at the design stage and in operating conditions should be selected based on the comprehensive and complex assessment of fuel efficiency and pollutants emissions, taking into account both design and operational factors.

2 Technological Measures to Reduce Fuel Consumption

First of all, it is possible to decrease CO_2 emissions by means of reducing fuel consumption. The technological measures aimed at reducing fuel consumption in traditional internal combustion engines can be roughly divided into improving a particular engine design, keeping engine revolutions within the energy-efficient performance range, and optimized energy management. These measures are complemented by the reduction in car weight, rolling resistance and air resistance along with the measures aimed at improving driving skills [15].

2.1 Improving Engine Design and Transmission Technology

As far as optimizing the combustion process is concerned, one should distinguish between diesel and gasoline engines. In the case of gasoline engines, it is possible to significantly save up to 20% of fuel when using direct-injection engines in combination with stratified charge or variable valve timing (VVT) technology, innovative cylinder cutout technologies and reducing the idle speed, especially in the adverse conditions of partial throttling [16]. However, because of higher NO_x emissions, direct fuel-injection gasoline engines require that NO_x emissions be cleaned by catalytic converters, in this case it is possible to obtain the composition of exhaust gases close to that of diesel engines emissions.

Diesel engines consume 15–20% less fuel than gasoline engines. However, CO_2 emissions from the combustion of one liter of diesel are about 13% higher than from one liter of gasoline. The lower level of diesel consumption is due to a much higher compression ratio and direct fuel injection [15]. Despite burning with excess air, rapid fuel injection can still lead to localized starvation and hot spots, which leads to soot and NO_x emissions. Therefore, the further progress of diesel engines involves improving the fuel injection processes in order to get more homogeneous mixtures and ultimately reduce emissions [17].

It should be also noted that a slight reduction of about 2% in fuel consumption can be obtained by improving the exhaust gas recirculation.

In the long run, the combustion processes in gasoline and diesel engines are expected to converge [18].

It is well known that both engine types achieve the best efficiency level in a certain performance range. This range can be provided by optimum transmission parameters. In this case, automatic gearboxes with a wider gear range (6 or 7 gears) and gear changes, supported hydraulically or electronically, can reduce fuel consumption by about 10% [19]. Automatic gearboxes can be further improved to use the continuously variable transmission (CVT), which can additionally save about 8% of fuel [20].

2.2 Energy Management and Hybridization

In urban conditions, the engine power of transport vehicles is not used for about 45% of the operation time. In such operating conditions, an automatic start-stop system which uses the flywheel to start and stop the engine can save about 25% of fuel [21].

A prospective direction is further hybridization (strong or parallel hybrid) when an electric motor with sufficient power for car self-feeding is installed next to a conventional internal combustion engine. This allows for three different operation methods: an internal combustion engine, an electric motor, and a combination of both.

The electric motor is usually designed for city driving, and the internal combustion engine—for motorways and other trips over longer distances. Hence, the internal combustion engine may not be used when the throttle is partially open: although the performance requirements are lower in this case, the internal combustion engine can still operate at a favorable efficiency level, and excess energy is used to recharge the battery. It also allows for the purposeful reduction of the internal combustion engine size, its weaknesses with a partially open throttle can be compensated by the electric motor. The parallel hybrid provides regenerative braking, that is, the braking energy is recovered and stored in the batteries.

Along with reduced emissions (except NO_x), the advantages of a parallel hybrid over gasoline and diesel engines contribute to a potential reduction in fuel consumption from 25 to 34% [22].

The disadvantages of hybrid vehicles are their dual energy storage and dual engines that affect the weight and value of the vehicle.

2.3 Vehicle Design

Since the increase in the performance indicators of the internal combustion engine is almost exhausted, a promising direction for decreasing fuel consumption is to reduce the car weight and increase the aerodynamic properties of the body.

Expanding the use of light steels, aluminum, and plastics creates opportunities to reduce car weight without compromising safety and comfort. The authors of [23] state that the reduction of car weight by 10% leads to the decrease in fuel consumption by 5.6–8.2%. In the foreseeable future, up to 2030, it may be possible to reduce car weight by 28–30% [24].

Plastics are flexible materials with low thermal conductivity, high chemical resistance, good dielectric and optical properties, and high corrosion resistance. They can damp and suppress vibrations. This explains their widespread use in the automotive sector.

The modification of polymers, in particular, the structural and chemical modification with reactive compounds, is one of the effective methods of regulating the structure and properties of polymers as well as creating composites that combine the valuable properties of polymers and fillers, can be easily processed into products of complex shape and have special properties, characteristic of a particular filler. This combination significantly extends the application field of these materials.

At the same time, the increased production and use of plastics result in the accumulation of huge plastic wastes. Plastics and plastic fibers are not environmentally friendly, they have high carbon composition, cause environmental pollution and do not degrade. Hence, the problems of recycling plastic products and environmental issues require comprehensive scientific studies to produce environmentally friendly and biodegradable composite materials from renewable raw materials.

Composites containing natural fibers (NF) and natural polymers play a key role among different types of composites. At present, the most efficient way of making environmentally friendly composites is to use natural fibers as reinforcement.

Polymer composites reinforced with natural fillers were used to replace widespread materials in several industries, including the automotive industry.

Automobile foams and extruded polymers are also widely used nowadays [25]. In particular, about 150 plastic products with a wide range of physical characteristics are used in car showrooms, and foam production for the automotive industry worldwide is 1.7 million tonnes per year.

A promising trend is also the use of polymer nanocomposites based on natural fillers, which, due to their lower density, help reduce the weight of materials and generally meet the requirements of the automotive industry and in some cases even exceed them (Fig. 2).

Nanocomposites are a class of polymer materials that have excellent mechanical, thermal and technological properties and can be used to replace metals in the automotive and other industries (Table 1). Due to the peculiarities of nanodimensional

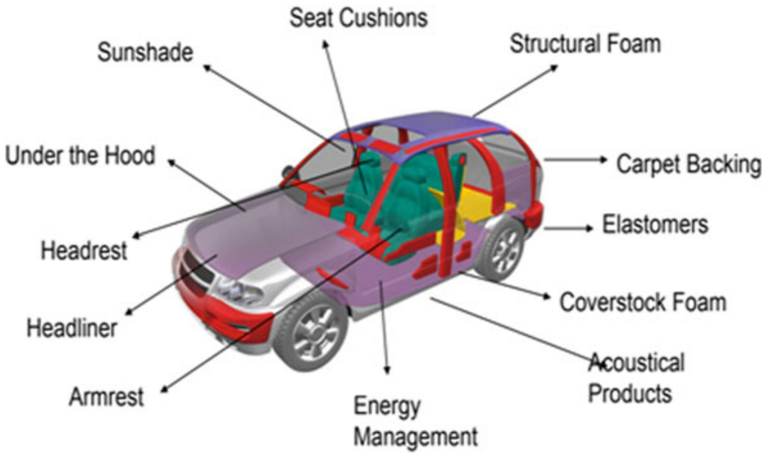


Fig. 2 The use of polymer restorative composites [26]

Table 1 Properties of different materials [23]

Material	Modulus of elasticity (GPa)	Tensile strength (GPa)
Nanocellulose	150	9.5
Kevlar 49	125	3.5
Carbon fiber	150	3.5
Carbon nanotubes	300	20
Stainless steel	200	0.5
Oak	10	0.1

particles and a very high surface-to-volume ratio, they have a unique combination of multifunctional properties that are not characteristic of their conventional composite analogues [23].

These multifunctional nanocomposites not only have great mechanical properties, they also demonstrate an excellent combination of optical, electrical, thermal, magnetic and other physicochemical properties. It is believed that the interaction between nanoparticles and polymer matrices at the molecular level and the presence of the nanoparticle-polymer interface play a major role in influencing the physical and mechanical properties of nanocomposites. These composites also have distinct advantages (specific strength and modulus of elasticity) compared to fiberglass and mineral fiber, which make them more competitive in the automotive industry.

Parts made from nanocomposites provide rigidity, strength, durability and reliability at the metal level, and in some cases they even exceed them. They have high corrosion resistance, noise absorption, enhanced modulus of thermal resistance, and dimensional stability. Nanocomposites can replace metal and glass components in the near future. They can help the automotive industry to take a leading position in saving fuel and produce more durable vehicles of a higher quality.

The commercialization of polymer nanocomposites began in 1991 when Toyota Motor Co. was the first to introduce to the market nylon-6/clay nanocomposites used to manufacture timing belt covers as parts of engines for its Toyota Camry vehicles. About the same period, Unitika Co. from Japan introduced the nylon-6 nanocomposite for engine covers on Mitsubishi GDI3 engines made by injection moulding. These covers are 20% lighter than their counterparts and have excellent surface finish [27].

Elastomeric nanocomposites are also getting widespread in the automotive industry, especially for tire production. They have lower rolling resistance and weight and therefore demonstrate excellent fuel saving rates [28]. The main drivers for using these materials are the increasing demand for fuel utilization efficiency, strict automotive safety standards, increased durability and noise reduction. For example, replacing elastomer in the traditional inner liners for tires with nanocomposite inner liners leads to the reduction in fuel consumption by approximately 2%. Major tire manufacturers involved in the development and manufacturing of nanocomposites are Yokohama Tire Corp. (Japan), Pirelli SpA (Italy), Goodyear Tire & Rubber Co. (USA), Continental AG (Germany), InMat Inc. (USA) etc. The elastomeric nanocomposite tire models are also used by Goodyear UltraGrip Ice+, Continental EcoContact5, Michelin Energy Saver and Pirelli Cinturato P1.

Green nanocomposites or biodegradable nanocomposites (cellulose clay-reinforced bioplastics) are the next generation of materials used in automobiles. They have the potential to replace the existing non-biodegradable thermoplastic oil-based nanocomposites.

Despite the advantages of polymer composites reinforced with natural fillers, their wide use in the automotive industry still has some factors, mainly related to the economic production indicators [29], which impede their widespread commercial adoption. This trend can be improved by the increased productivity and environmental friendliness. For example, fillers can reduce the negative impact of non-biodegradable polymers [30]. In general, the market for polymer composites is strengthened by natural fillers for the automotive industry. It is a multi-billion business in which the manufacturers and engineers are in constant search in order to prepare more competitive materials, thereby increasing their profitability [31]. In particular, at present, the European market for polymeric materials contains 10–15% of wood plastics and composites made from natural fiber [32].

In addition, the use of natural fibers for the production of polymer composites creates the opportunities for general employment in rural and less developed regions, thereby helping to achieve the UN sustainable development goals, namely poverty eradication, promotion of the inclusive and sustainable industrialization, stimulation of innovations, creation of sustainable cities and communities, and responsible production and consumption. Therefore, natural fibers will play a vital role in the socio-economic development of society.

A significant fuel economy in ICE motor cars can be obtained by reducing the aerodynamic body resistance and rolling resistance. As shown in [33], due to these factors, the specific fuel consumption can be reduced by 12% by 2030, inter alia by improving the aerodynamic properties of cars by 4.4% and reducing the rolling resistance by 6.7%. Besides, the effect of the start-stop system use should be also taken into account, as it helps to reduce the engine idling losses by almost 60% [34].

3 Peculiar Features of Biofuels Production

The biofuels made from different biological raw materials should be highlighted among alternative renewable fuels. The obvious advantage of these fuels is a virtually inexhaustible raw materials base used for their production and excellent environmental qualities. Biofuels can technically replace oil in all modes of transport with the existing fueling infrastructure. Biomass resources can be also used to produce decarbonized synthetic fuels, methane and LPG. Therefore, some key factors can be singled out as the main prerequisites for the development of biofuels industry.

The **first factor** is the need to combat global climate changes caused by increased greenhouse gas emissions into the atmosphere, mainly of carbon dioxide CO_2 as well as SO_2 and NO_x. The increase in carbon dioxide emissions into the atmosphere is significantly associated with the increase in global energy consumption, mainly with the use of fossil energy sources, such as gas, oil, coal, etc.

The **second factor** is the desire to improve the countries' economic security and to reduce their strategic dependence on the foreign supplies of fossil fuels.

The **third factor** is the development of internal competition, diversification of countries' economies, optimization of production cycles and supply chains, and the introduction of energy efficient and resource-intensive technologies.

At present, biomass ranks fourth in the global energy system, accounting for 10–14% or 51 EJ of the global energy supply [35]. The world market for biofuel production is constantly developing due to the existence of state programs for the development of bioenergy. In the coming decades, the contribution of bioenergy to the world fuel and energy production will continue to increase. Its growth is on average 3.3% per year [4].

Nowadays there are several predictable scenarios for the worldwide energy development and use. According to the World Energy Council (WEC) estimates, by 2050 energy consumption will increase more than twice compared to 1993, and over 40% of energy needs will be covered by renewable energy sources, among which the proportion of bioenergy will be 32%.

However, the development of current trends in the global biofuel market is accompanied by the contradictions between its participants at all levels—starting from groups of states and ending with individual economic entities and consumers. In this case, the economic, environmental and social effects of biofuel implementation remain controversial. These factors can be a significant impediment to the development of biofuels market and, therefore, require an in-depth analysis of all aspects of the impact of biofuels production both on the economies of individual states and the world as a whole.

Biofuels are defined as a kind of fuel produced from renewable organic biomass through physical and chemical processes with zero net CO_2 emissions. Biomass is an organic material that can store chemical energy produced by photosynthesis; it may be timber, wood waste and many agricultural by-products [36].

Biofuels are an alternative to traditional oil-derived fuels. The ever-increasing demand for them in the long term can dramatically change the situation in the global energy market. At the same time, new vehicles capable of consuming both traditional fuels and mixtures containing over 80% of biofuel are increasingly being produced in the world. Nowadays, the rates of biofuels production increase are far behind the increasing demand for them.

At present, more than 40 countries of the world produce biofuels. The current leaders of biofuel production are the United States, Brazil and the European Union. About 85% of the world's biofuel production is concentrated in these countries. The largest proportion in production (48%) is in the United States of America. The rapid development of China's biofuels industry should be also highlighted [37].

In 2004, the increasing global demand for alternative energy types, rising oil prices and tax incentives contributed to the fact that many countries around the world started expanding their potential for biofuels production. The overall economic growth, production subsidies and legislative support helped to rapidly increase investments in the biofuels sector, especially in 2004–2007, and the share of biofuels in the total fuel consumption in several countries of the world.

Global biofuels production increased sevenfold—from 16 billion liters in 2000 to 110 billion liters in 2012. At the same time biofuels made up only 2.3% of the total amount of liquid (motor) fuel used. The rates in Brazil (20.1%), the United States of America (4.4%) and the European Union (4.2%) exceeded the world average.

Within seven years (from 2000 to 2007), the bioethanol fuel production tripled and exceeded 60 million liters, with Brazil and the United States accounting for the bulk of this increase. During the same period, the biodiesel production in the EU countries saw a more significant growth, resulting in the production increase from less than 1 billion liters to almost 11 billion liters, i.e. by 11 times.

The EU has three major biodiesel producing countries—Germany, France and Italy. France and Germany are the largest consumers of biofuels in the European Union.

It should be noted hat biofuels are important for two reasons. Firstly, biofuel is the only renewable energy source that can provide about 27% of the world's transport fuel, which is currently made from fossil fuels [38]. The use of biofuels can lead to a reduction of 2.1 Gt of CO_2 in the atmosphere per year. Secondly, biofuels production can create wealth and contribute to the sustainable improvement of human well-being both now and in the long run. In addition to greenhouse gas emission reduction [39], there is substantial evidence that bioenergy brings numerous benefits that can offset environmental issues related to fossil fuels, intensive food production and urbanization [40]. Besides, the biofuel industry development can promote agricultural development and benefit farmers through its utilization of waste from food crops, bioenergy crops and other biomasses. The examples range from pollution abatement in urban centers to improving the agricultural efficiency in rural areas, which benefit from the improved access to energy and poverty alleviation.

Nowadays about 90% of the world's biofuel consumption is accounted for by liquid fuels—bioethanol and biodiesel. Other biofuels are also used, such as pure vegetable oil and compressed biomethane, although their market presence is quite limited. The world production of liquid biofuels (i.e. ethanol, biodiesel) has been growing rapidly in recent decades. According to the International Energy Agency estimates, in 2050 the share of biofuels in the transport sector will increase to 27% [41].

According to different expert estimates of bioenergy development prospects, there is a potential for the sustainable increase in the volumes of timber processing in Europe. The results of expert reviews and estimated figures in the European Forest Sector Outlook Study for the period 2010–2030 show that the use of wood biomass for bioenergy will nearly double by 2030 (from 435 million cubic meters in 2010 to 859 million cubic meters in 2030) [42].

At present, in the EU countries, the potential reserves that can be processed into energy are estimated at 277 million cubic meters of ground vegetation biomass and 308 million cubic meters of subsurface biomass, the possible total growth may be up to 913 million cubic meters in the long run. Thus, theoretically, the EU can cover its internal raw material needs for bioenergy production.

If the existing trends in bioenergy development in the EU continue, by 2030 the competition for wood biomass will significantly intensify, affecting biofuels markets both within the EU and in exporting countries. Wood biomass production technologies will be increasingly developed through the intensive use of land resources capacity during the long-term cycle of forest cultivation (intensification of forest use on woodlands) and short-term cycle of forest cultivation (establishment of plantations on non-forest lands).

If the automotive industry has been trying to replace gasoline engines with hybrid or fully electric engines for several years, then this process is just beginning for air and maritime transport. It should be noted that airlines switch their fleet to biofuels,

Table 2 Types of raw materials and end products of different generations of biofuels

Generations of biofuels	Raw material	Biofuels
First generation	Sugar beet, sugar cane, corn, wheat, potato, soybean, sunflower, rapeseed, palm oil, animal fats, vegetable oil	Bioethanol, biodiesel, biomethane
Second generation	Wood waste, energy crops, straw stalks, corn stover, sugar cane, organic wastes	Bioethanol, biobutanol, biodiesel, synthetic fuels
Third generation	Algae	Biodiesel, hydrogen, bioethanol, biomethane, synthetic fuels
Fourth generation	Algae, other microbes, by-products, carbon dioxide	Bioethanol, hydrogen

and aviation companies try to develop electric airplanes in order to reduce greenhouse gas emissions and running costs.

According to the innovation degree, the biofuels made from biomass for use in automobile engines are divided into the first, second, third and fourth generations [43].

Table 2 shows the types of raw materials and end products of different generations of biofuels.

3.1 First-Generation Biofuels

First-generation biofuels include bioethanol, produced from the crops rich in sugar (sugar beet, sugar cane) and starch (corn, wheat, cassava), and biodiesel from oil crops (soybeans, sunflower, rapeseed, palm oil) or animal fats and pure vegetable oil. In most cases, these types of raw materials can be also used as foods and feeds [43].

Bioethanol is one of the most important products in modern bioeconomy. About 85% of the global production of liquid biofuels comes from it. In recent years, the worldwide bioethanol production has reached the level of about 106 million m^3 per year (Fig. 3). The two largest manufacturers of this product, the United States and Brazil, account for about 90% of the total production, with the rest coming mainly from China, Canada, the EU and India.

Fuel ethanol is obtained by means of fermentation of sugars (glucose, sucrose) with alcohol yeast *Saccharomyces cerevisiae* in an oxygen-free environment.

$$C_2H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Ethanol increases the knock resistance of gasoline and its combustion efficiency. However, traditional 96% alcohol is not added to gasoline. The dehydrated ethanol

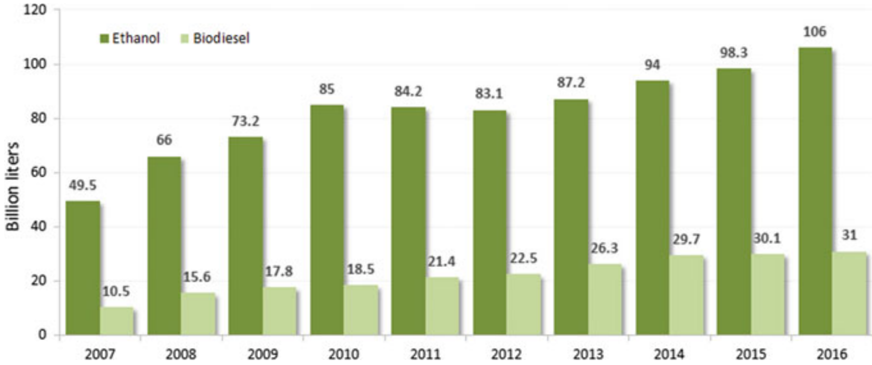


Fig. 3 Dynamics of the global ethanol and biodiesel production [44]

is added instead, because it does not emulsify. Zeolites, azeotropic distillation with cyclohexane, and membrane technologies are used to dry alcohol.

At present, biodiesel is gradually becoming one of the most important fuels. By 2020, the share of biodiesel in the total motor fuel consumption can reach 20% in Europe, Brazil, India and China. In case of active state support, creation of a favorable investment environment and taxation system for the industry, this figure may be even higher. Nowadays, about 90% of the world biodiesel consumption is accounted for by Europe, but the biodiesel industry of the United States is the fastest growing industry in the world.

From the chemical point of view, biodiesel is a mixture of methyl (ethyl) esters of saturated and unsaturated fatty acids. At present, the largest volume of biodiesel is produced by the method of transesterification of vegetable oils and fats to esters and fatty acids.

$$
\begin{array}{lcccc}
CH_2OCOR^1 & & CH_2OH & & CH_3OCOR^1 \\
| & & | & & | \\
CHOCOR^2 & + 3\,CH_3OH = & CHOH & + & CH_3OCOR^2 \\
| & & | & & | \\
CH_2OCOR^3 & & CH_2OH & & CH_3OCOR^3
\end{array}
$$

The transesterification process is carried out through reaction of alcohol with triglycerides in the presence of a homogeneous catalyst, usually an acid, alkali or enzyme, to obtain glycerol and esters of fatty acids. Although methanol is mainly used in the industry, ethyl, propyl, butyl and amyl alcohols may be also used as esterification agents. The resulting reaction mixture is separated in separators or in settling tanks. As a result, a mixture of fatty acid methyl esters (biodiesel fuel) and glycerol phase ("black" glycerol) containing 45–50% of glycerol, unreacted methanol, saponification products of fats and other impurities are obtained. Refined glycerol is used for the production of detergents, and after deep purification it is used in pharmacy.

A number of authors treat biogas as the first generation of biofuels [43]. Biogas has a special status among all renewable energies, because it has manifold uses in different fields of the power industry. Biogas production is a well-established technology that uses a wide range of residues in the form of raw materials.

Biogas is produced as a result of anaerobic biodegradation of organic biomass, in which organic matter is decomposed by microbes in the absence of oxygen (Fig. 4). Biogas, generated as a product of the metabolic action of methanogenic bacteria, consists mainly of methane (55–75%) and CO_2 (25–50%). Several methods have been proposed to extract CO_2 from biogas, the most common being extraction with solvents, activated carbon adsorption, membrane filtration and cryogenic separation [45].

Different types of raw materials are used for biogas production. These include agricultural crops, sewage sludge, solid plant waste, leaves, grass, seaweed, animal waste and microalgae.

Biogas is a valuable energy carrier, because it can be used for various purposes and with high efficiency. The use of biogas as a motor fuel provides a significant saving of fuel and energy resources. The experience of operating cars using biogas as a motor fuel proves the possibility of its use in traditional vehicle designs. Due to the simple, reliable and proven technology, biogas has all the necessary characteristics to become one of the most efficient and cost-effective fuels obtained from renewable sources.

Like natural gas, before it is used in the internal combustion engine, biogas is enriched (up to 95% of methane content), purified, dried and compressed. The purified biogas is usually delivered to fueling stations by special tank trucks or by pipelines.

It is worth noting that biomethane can be turned into renewable fuel—hydrogen.

The production of biomethane gives a higher energy yield per hectare than the production of bioethanol or biodiesel (Fig. 5). The production residues are nutrients and microelements that return to farmlands and increase their productivity. However,

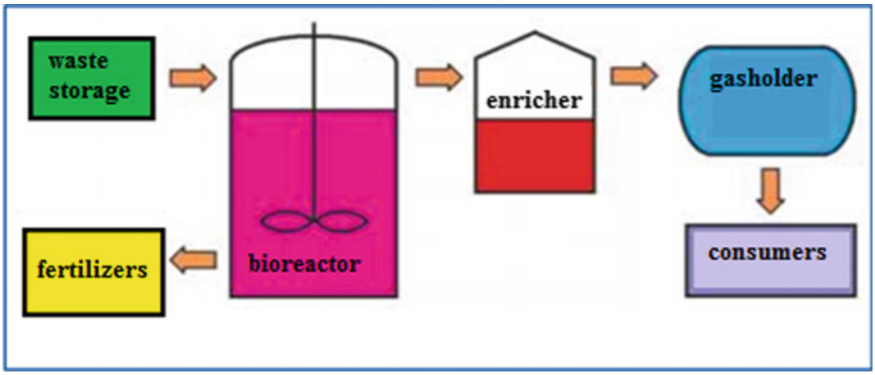


Fig. 4 Scheme of biogas production [45]

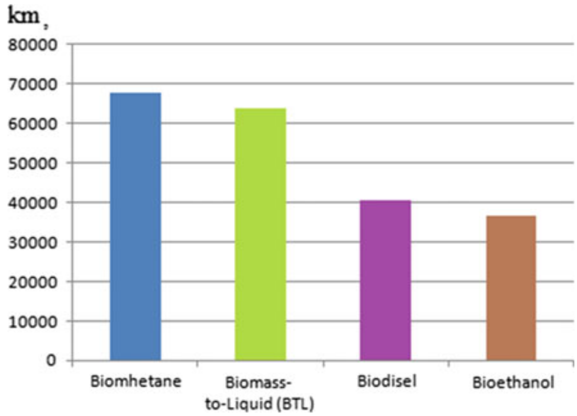


Fig. 5 Distance driven by a motor car with fuel obtained from 1 ha of cultivated land [46]

methane leaks can be a problem. Although methane is a valuable fuel, either in the form of biomethane or natural gas, it is also a greenhouse gas with a global warming potential 25 times higher than carbon dioxide. For this reason, special measures should be taken to minimize losses during production, storage and transportation.

The main disadvantage in the production of first-generation biofuels is the need to use high-quality arable land, different heavy agricultural machinery, fertilizers and pesticides.

3.2 Second-Generation Biofuels

Second-generation biofuels are the next step in the processing of biological raw materials, allowing for the use of a wider range of biomass, the main component of which is lignocellulose. The global production of plant biomass is 200×10^9 tonnes per year. 90% of the biomass is accounted for by lignocellulose. The percentage composition of lignocellulose components may vary depending on the type of raw material, and each component of lignocellulose, if properly processed, can be used in biofuel production.

However, the processing of cellulosic raw materials is more complex than the processing of sugar or starch. Therefore, the production of second-generation biofuels requires more complex fuel extraction and processing technologies. It is worth noting that there may be competition between the potential use of cellulosic materials to produce liquid motor biofuels and solid biofuels to generate heat and electricity.

The commercial production of second-generation biofuels remains relatively low today. Support for policies to promote the production of advanced biofuels from lignocellulosic biomass-based raw materials, such as wood and agricultural residues, have encouraged the development of commercial pilot projects in Europe and the US.

In 2012, the production of modern biofuels in the USA from lignocellulosic raw materials reached 2 million liters. China made progress in the production of second-generation biofuels too and produced in 2012 about 3 million liters of ethanol from corn cobs for use in gasoline blends. At present, several demonstration plants with small volumes of final products operate in Europe.

Mainly biochemical and thermochemical methods are currently used to produce second-generation biofuels.

The biochemical methods are based on the hydrolysis of pre-treated lignocellulosic material with enzymes or acids into xylose C_5 and glucose C_6, which is followed by their fermentation into bioethanol [43].

The most effective and promising hydrolysis method of pre-treated lignocellulose is the enzymatic method, which, in general, does not produce any toxic by-products. It involves cellulases and hemicellulases of prokaryotic and eukaryotic microorganisms, mainly fungi.

Thermochemical biofuel production technologies have the advantage of producing hydrocarbons that are fully compatible with existing fuels, which is very important for infrastructure development and creating fuel blends (traditional fuel + alternative fuel). In addition, thermochemical processes allow the production of synthetic biofuels—gasoline and diesel.

Synthetic fuels have excellent consumer properties. Therefore, they can be used not only for modern internal combustion engines, but also for the future prospective engine designs. Methanol, dimethyl ether, methane and hydrogen can be obtained in this way too.

A promising type of synthetic gaseous fuel produced from synthesis gas is dimethyl ether (DME). Despite the fact that DME is inferior to traditional diesel in energy content, lubricity and viscosity, it has some undeniable advantages. High oxygen content and the absence of carbon-to-carbon bonds in the molecular structure of the ether result in its effective combustion in diesel engines. Compared to petrodiesel, DME has a higher methane number (55–60), low boiling (−25 °C) and ignition (235 °C) temperatures, and does not contain sulfur and its compounds, which in total contributes to the significant reduction of soot, nitrogen and sulfur oxides emissions in the exhaust gases, overall reduction of noise levels and increased engine life. In addition, this fuel has excellent starting characteristics at low temperatures.

The disadvantages of this fuel are low kinematic viscosity (leakage tendencies) and poor lubrication properties. Sealing may be also required, because dimethyl ether is a strong solvent for most rubber products.

One of the main areas of the biomass thermochemical conversion involves using the pyrolysis process, which results in the formation of pyrolysis gases and liquid fraction—bio-oil and solid coal. Bio-oil is mainly used for the production of transport biofuels.

Bio-oil is a thick dark brown resinous liquid with an acid-smoke smell, which is similar in appearance to the traditional fossil oil. Depending on the raw material, the modes of pyrolysis process and the presence of microorganisms, the color of the liquid may change and turn dark red-brown, dark green and almost black [47].

The high content of water in bio-oil complicates its flammability. The increased acidity of bio-oil causes corrosion of some systems during storage and use (tanks, pipelines, fittings, nozzles, etc.) and requires the use of anti-corrosion materials. In addition, bio-oil is instable and may change its properties over time (viscosity growth, phase separation, and the formation of polarized deposits), the same happens when it contacts warm air. Different physical and chemical methods are used to improve the quality of bio-oil.

At present, mainly the chemical upgrading of bio-oil and the co-processing of bio-oil with petroleum products at the oil refinery are used to obtain transport biofuels in the pyrolysis process [48].

The chemical upgrading of bio-oil involves its hydrotreatment to the minimum oxygen content and the hydrocracking of the heavy part of the upgraded liquid. After that, the distillation of the resulting mixture and its separation into gasoline and diesel fuels take place. The process scheme is shown in Fig. 6.

The studies conducted by BTG staff together with the scientists from the University of Twente showed that the biodiesel obtained by direct upgrading could be blended with traditional diesel in the proportion of 25% to 75% respectively, and the resulting mixture could be successfully used for fueling cars [49].

Nowadays, the co-processing of renewable and natural raw materials on standard oil refining equipment is of particular interest (Fig. 7). The co-processing is the simultaneous transformation of biogenic raw materials—bio-oil and intermediate petroleum products, such as vacuum gasoil (VGO)—using the existing refinery processing units.

The co-processing in fluid catalytic cracking units is a new and promising way of converting bio-oil into renewable gasoline and diesel. Current studies are mainly

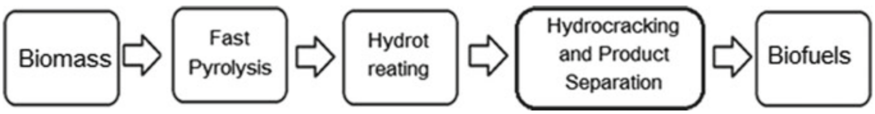


Fig. 6 Scheme of turning biomass into liquid fuels by upgrading the bio-oil [48]

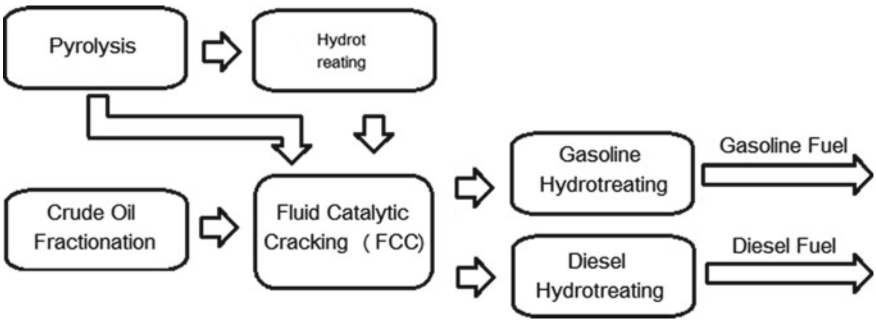


Fig. 7 Scheme of the fluid catalytic cracking unit for co-processing [48]

aimed at unlocking the potential of this technology and show that co-processing can provide significant potential for using the existing processing infrastructure for biomass processing, mainly lignocellulosic raw materials, and increase the supply of biofuels to the market [50]. For example, in the United States of America, there are 110 fluid catalytic cracking units currently in operation, the use of which could provide the production of more than 8 billion gallons of biofuel (more than 30 billion liters) at the existing refineries. [51]

The authors of [52] carried out research and established the technical possibility of the direct use of crude bio-oil in the amount of up to 20% for co-processing. It is worth noting that the co-processing of bio-oil in combination with petroleum products does not require the construction of new plants. It reduces the dependence on fossil oil and can pave the way for the intensive introduction of biofuels to the market. The obtained biofuels have good operational characteristics and their use practically does not require changes in the fuel consumption infrastructure.

3.3 Third- and Fourth-Generation Biofuels

The definition of “third-generation biofuels” generally denotes the biofuels that do not compete with either feed grains or land. The most commonly accepted definition of third-generation biofuels is fuels produced from the algae-derived biomass [43].

Algae are the fastest growing plants in the world. They can double their weight several times a day, contain a record amount of oil and have no analogues in the plant world according to this indicator. Up to 40 harvests per year can be taken from one biofuel algae cultivation site, and about 80% of the organic matter generated on Earth every day is accounted for by algae. Theoretically, more than 15,000 L of lipids per year can be obtained from 1 ha of phytoplantation.

Microalgae—both the simplest unicellular and large seaweeds—are used for industrial processing. The former are used to produce biodiesel and hydrogen, the latter—to produce bioethanol, biomethane and liquid synthetic fuels by the Fischer-Tropsch process.

The peculiarity of algae production is the ability to change the quantitative and qualitative composition of lipids (variability), depending on the culture medium, light and temperature. As there are many lipids in cell walls, it is possible to remove them by non-toxic solvents without disrupting cells’ viability. Lipids can be also extracted by centrifugation, which, after their separation, allows the biomass to be placed in a nutrient medium for the re-accumulation of hydrocarbons. It is especially important that algae can be cultivated in all conditions of all climatic zones. Carbon dioxide is also used for algae cultivation. It is passed through the culture medium, which reduces its content in the atmosphere and contributes to the global warming slowdown.

In addition to algae cultivation in open ponds, there are technologies for growing them in bioreactors, which is a better method to perform research and implement new and innovative production projects. Although these systems are more expensive in production and operation, they allow for the creation of a controlled environment to optimize the growing process: temperature, pH, gas level, uniform mixing, and sufficient light. Besides, bioreactors can provide for the cultivation of certain algae species without the competitive effect of other species, which is rather problematic in open ponds.

In general, microalgae biodiesel has two major advantages over the production of vegetable oil biodiesel. First, algae contain a large amount of polyunsaturated fatty acids that allow biodiesel not to lose its fuel properties at low temperatures, so diesel engines can work in winter. Second, the yield of fuel from microalgae is 20–30 times higher than from vegetable oil crops when grown on the same area.

Most third-generation biofuels are planned to be produced by converting the organic matter into fuel. However, there is an alternative approach based on the fact that some algae inherently produce ethanol that can be collected without destroying the plant itself. Thus, the photosynthesis accumulation of solar energy, CO_2 deposition and ethanol production occur during one process [53].

The production of molecular hydrogen by microalgae is currently at the stage of experiments and pilot projects. It is an absolutely clean fuel, characterized by the high calorific value of 143 kJ/g. It has high energy intensity, which is 3–5 times higher than the same indicator of gasoline and oil, and universal energy properties: reducing agent, energy carrier and fuel. The chemical and electrochemical methods for producing H_2 are not economical, so it is more rational to use the microorganisms capable of releasing hydrogen. Aerobic and anaerobic chemotrophic bacteria, purple and green phototrophic bacteria, cyanobacteria, various algae and some protozoa have this capability. Their use is of particular interest as they are more efficient in converting solar energy than higher plants.

The long-term benefits of hydrogen fuel as one of the substitutes for petroleum products were proved by the innovative programs, approved by the governments of some states, and a larger fleet of hydrogen vehicles and number of gas stations.

Thus, at present, algae are the most dynamic and high-energy plants. They can become the basis for the large-scale production of motor biofuels, thereby creating a basis for sustainable energy development of the future.

Hydrogen is considered to be a promising alternative in the long run (by 2030). Hydrogen produced from biomass, which can be used to drive motor vehicles with fuel cells or internal combustion engines, is sometimes considered to be another type of third-generation biofuels.

At present, there are all prerequisites to believe that hydrogen, just like biomass, can compete with fossil fuels. The transition from an oil-based energy system to a hydrogen economy requires the construction of many new hydrogen plants and gas stations. The new infrastructure should cater to the emerging demand for hydrogen and use the existing infrastructure, for example, gas pipelines and railways, to minimize the set price.

The early introduction of a certain hydrogen technology can dominate the market, provided there is appropriate infrastructure. For example, if natural gas became the dominant fuel for hydrogen production, a more complex pipeline network could be built to facilitate the transportation of gas for hydrogen production. The same system could be used to transport synthesis gas produced by coal or biomass gasification. In this case, it would be possible to reduce the costs of hydrogen production and make the hydrogen-based gas technology dominant [54].

The designs of hydrogen infrastructure and systems should comply with the existing infrastructure for the transportation of natural gas, coal, biomass, water and maybe other renewable energy sources [55].

The choice of raw materials for hydrogen production can also depend on time and prices. If the demand for natural gas increases, prices will rise and alternative technologies can become competitive [56].

The latest achievement in biofuels production is the fourth-generation biofuels. The production of this fuel type uses special living microorganisms that over time will be able to produce biofuel products with photosynthetic cells (more precisely, several cycles of photosynthesis). The microorganisms will use carbon dioxide to support their life processes [57]. It is believed that metabolic engineering of algae for biofuels production has great potential for producing sustainable and clean energy.

There are special electrotrophic microorganisms capable of using electric current to convert carbon dioxide from air or seawater into organic molecules. These microorganisms can be combined with any source of energy: nuclear and thermal power plants, renewable energy. Such developments in the field of alternative energy will help to minimize the consumption of organic natural resources and will lead humanity to a new and productive stage of the energy-efficient development [58].

Summarizing the analysis, it can be concluded that the above-mentioned fuel generations have their advantages and disadvantages (Table 3) and still have considerable potential for improvement.

Table 3 Advantages and disadvantages of the biofuels of different generations

Generation of biofuels	Advantages	Disadvantages
First	Use of simple production technologies, established commercial production	Competition for land with food crops, the need to use high-quality arable lands
Second	Do not compete for land with food crops, use marginal lands for the cultivation of energy crops	The need to develop high-level technologies for cost-effective processing
Third	No land use required; ponds, seawater, sewage water and bioreactors can be used for biofuels cultivation.	High cost of photobioreactors
Fourth	High yield of algae containing a large amount of lipids, high carbon dioxide capture capability	The research is at an early stage, substantial investment is needed for research and pilot projects

3.4 Economic Aspects of Biofuels Production

The production cost of biofuels is the cost of raw material resources plus production costs, including capital cost of chemicals, enzymes, energy and operating costs. With the exception of ethanol from sugar cane in Brazil, the production costs of all first-generation biofuels in each country are substantially subsidized [59]. Higher costs of edible crops have made the first-generation biofuels (except Brazil) more expensive.

Due to the rapidly increasing demand for raw materials for biofuel production, the prices for some raw materials, such as corn in the the USA, have risen sharply. In view of this, the production of second-generation biofuels from low-cost raw materials is promising [33]. Based on the data from different studies, the comparison of the cost of different generations of biofuels and the cost of conventional fuels is shown in Fig. 8.

According to Fig. 8, corn ethanol has the minimum cost, and algae biodiesel has the maximum cost. In [49, 59], it is reported that the capital cost per unit of production capacity decreases with the increase in the capacity of processing plants. Usually the reduction of these costs is enough to offset the increase in biomass costs, resulting from the increased average transportation distances associated with larger production scales. Large production scales are more significant for the thermochemical process [59]. Ajanovic and Hass [62] report that under exisitng political conditions, mainly excise tax exemption, the economic prospects of first-generation biofuels are quite promising in Europe, but the main problems of this generation of biofuels are the lack of land available for growing raw materials and modest environmental performance. The commercial production of the first- and second-generation biodiesel is practiced in many countries (Table 4).

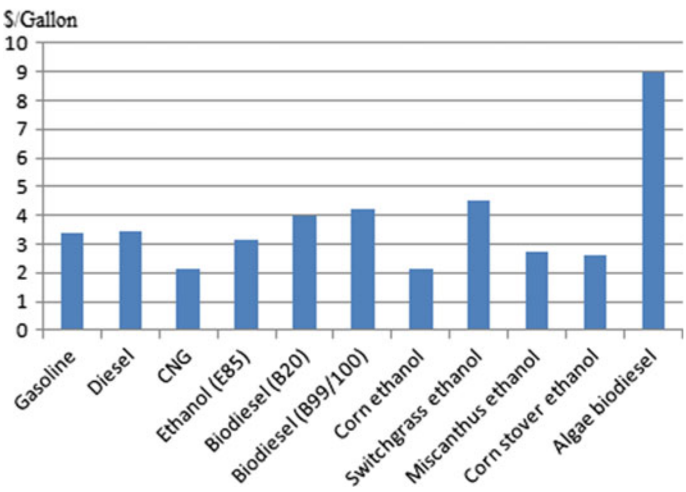


Fig. 8 Cost of biofuels from different raw materials compared to conventional fuels [60, 61]

Table 4 Biofuels at different levels of commercialization [43, 48, 61]

Generation	Type of biofuel	Commercial stage
1st generation	Corn ethanol	Commercialized
1st generation	Sugarcane ethanol	Commercialized
1st generation	Biodiesel (rapeseed, soyabean)	Commercialized
1st generation	Palm oil biodiesel	Commercialized
2nd generation	Cellulosic ethanol	Under research level
3rd generation	Algal biodiesel	Under research

An important indicator in the biofuels production is the net energy ratio (NER). This ratio determines the ratio of the amount of produced energy in MJ to the amount of consumed energy in MJ and indicates the commercial feasibility of the process. The values of net energy ratio for different fuels are shown in Fig. 9. In this case, the NER value less than 1 indicates that the production process is commercially unprofitable.

The authors of [65] studied the NER of the small-scale production of rapeseed and soybean biodiesel. They found that biodiesel made from soybeans was more energy efficient than rapeseed biodiesel because of the lower need for nitrogen fertilizers. However, rapeseed was a more productive raw material due to its higher oil content. The work [66] compared net energy consumption with greenhouse gas emissions of algae (Nanochloropsis) with soybean biofuels and fossil fuels, and found that algae biodiesel had 5% less greenhouse gas emissions than soybean biodiesel. Besides, it was noted that the NER of algae biodiesel was 43% lower than the NER of soybean biodiesel. Figure 6 shows that the NER for second-generation bioethanol is close to the NER of fossil fuels. The authors of [67] obtained the highest NER for cellulosic

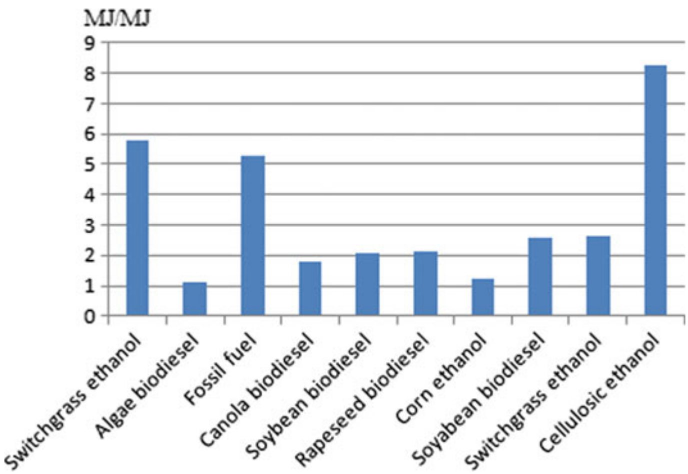


Fig. 9 Values of the net energy ratio for different types of biofuels [63, 64]

ethanol. Due to lower NER values (<1), the authors of [68] conclude that horizontal tubular photobioreactors (PBRs) and plane-type photosynthetic bioreactors are currently commercially unsuitable.

4 Biofuel Influence on Global Climate Change Mitigation

Although in the context of general power demands the biofuel production is small like before, at the same time it is quite significant in comparison with the modern level of agricultural production. In connection with this, possible ecological and social consequences of further increase of biofuel production should be recognized.

For instance, greenhouse gas emission reduction is among the specific goals of biofuel production support policy. An unpredicted negative influence on the land and water resources, as well as on the biodiversity, is regarded as a side effect of agricultural production as a whole, but it triggers special concern in regards to the biofuel. The degree of such influence depends on the way the raw materials for biofuel are conveyed and processed, on the scale of production, and especially on the discovered influence on the change of the nature of land use, intensification and international trade.

In many specialists' opinion, the replacement of fossil fuel with the fuel produced from biomass will make a significant positive impact on climate due to emission reduction of greenhouse gases, which constitute one of the reasons of global warming [69]. Bioenergy crops are capable of reducing and compensating greenhouse gas emissions by way of directly eliminating carbon dioxide from air during the process of their growth and accumulating it in their biomass and soil. Many of such crops are used not only for biomass production but also for the production of by-products, such as protein for animal feeds; this saves energy which would be spent on the production of feeds by means of other methods.

Regardless of such possible benefits, scientific investigations have proved that various kinds of biofuel differ significantly by greenhouse gas balance if compared with fossil fuels. Depending on the method of raw materials production and fuel manufacturing process, some crops can produce even more greenhouse gases than fossil fuel does [70]. For example, nitrogenous fertilizers emit nitrogen oxide. Moreover, greenhouse gases are also emitted at other stages of production of bioenergy crops and biofuel: in the process of production of fertilizers, pesticides and fuels used in agriculture, in the process of chemical processing, transportation and distribution up to their end use.

Greenhouse gases can also be emitted due to direct or indirect changes in the nature of land use caused by the expansion of biofuel production: for example, carbon release from the soil accumulated by woods or meadows, as a result of repurposing lands for cultivation of crops. For instance, if maize, which is cultivated for ethanol production, can reduce greenhouse gas emission approximately by 1.8 tons of carbon dioxide per hectare per year, and millet (potential second generation bioenergy crop) can achieve reduction by 8.6 tons per hectare per year, then the conversion of meadowland to the production of such crops can yield 300 tons of carbon dioxide per hectare, while in case of forests it constitutes from 600 to 1000 tons per hectare [71].

A life-cycle analysis is an analytical tool used for the calculation of balances of greenhouse gases. The balance of greenhouse gases is obtained as a result of comparing all greenhouse gas emissions during all stages of biofuel production and usage with all the greenhouse gases emitted during the production and usage of equivalent amount of energy of the respective fossil fuel.

With the help of a reliable, albeit complex, method, a thorough analysis of each chain link of value creation is carried out aiming at the assessment of greenhouse gas emissions (Figs. 10, 11).

The assessment of greenhouse gas balance starts from the determination of boundary conditions for a specific biofuel system, which is compared with the corresponding reference system, and in most cases, it is gasoline. Some kinds of raw materials for biofuel are also used for the production of by-products, such as seed cake, livestock feed, etc. In such cases, "eliminated" emissions of greenhouse gases are considered, which are compared with analogical stand-alone products or assessed based on the distribution method (for example, based on energy store or market price).

Greenhouse gas balances differ significantly for various crops and locations, and depend on the methods of raw materials production, treatment processes and application. Resources which were put in, such as nitrogenous fertilizers, and the way of electrical energy obtainment (for example, from coal or oil, in the form of nuclear energy), which are used in the process of raw materials treatment for their conversion

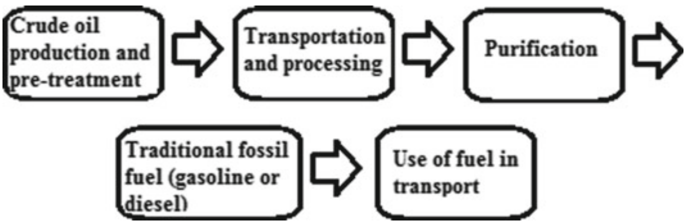


Fig. 10 Life-cycle analysis for fossil fuels

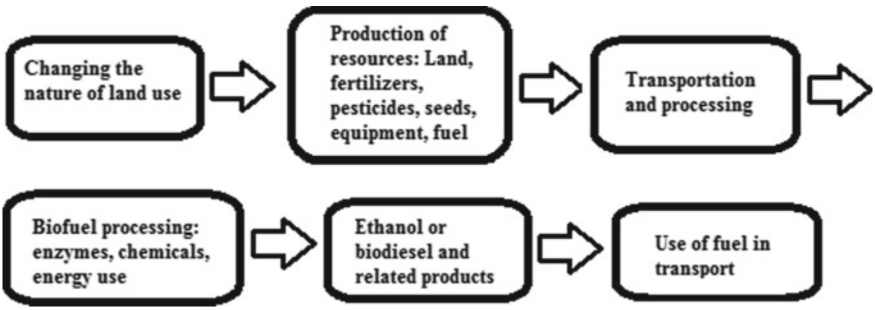


Fig. 11 Life-cycle analysis for biofuels

to biofuels, can cause the varying degree of greenhouse gas emissions and also be different in various areas (Fig. 12; Table 5).

The majority of currently existing investigations on biofuel conducted with the use of life-cycle analysis were dedicated to grain and oil crops in the European Union and the United States of America, as well as to sugarcane ethanol in Brazil.

Taking into consideration a big variety of kinds of biofuel, raw materials and technologies of production and treatment, one can expect the obtainment of an equally wide range of results during the calculation of emission reduction which is observed in reality.

The majority of investigations show that the production of the first generation biofuel from the existing raw materials will lead to emission reduction in the range of 20–60% if compared with fossil fuel under the condition of using the most effective systems (calculations exclude carbon emissions as a result of the change of land use nature). Brazil, which has a long-time experience in sugarcane ethanol production, demonstrates higher values of emission reduction.

The second generation biofuel, which still has a small commercial value, usually provides with 70–90% reduction of emissions in comparison with fossil diesel fuel and gasoline and also does not take into account carbon release due to the change of land use nature.

Some of the latest investigations show that the most distinct differences in the obtained results emerge due to the selection of different methods of by-products distribution and different assumptions about nitrogen oxide emissions and carbon release resulting from the change of land use nature. It is worth mentioning that a wide range of different methods is used for the execution of life-cycle analysis and, as mentioned above, some of them do not take into account a complex issue of changes in the land use structure. Measurement parameters and the quality of data used in the assessments must comply with the established standards. At the moment, there are efforts made, including also the ones within the framework of the Global Bioenergy

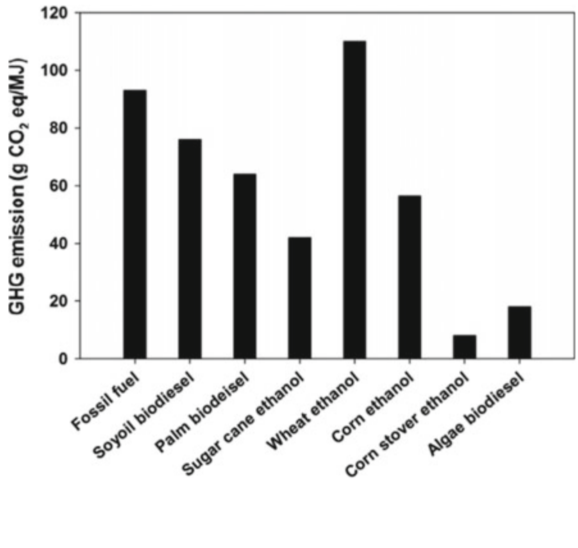


Fig. 12 Life cycle of GHG emission from different sources of biofuel [62, 72–74]

Table 5 Stages of life-cycle for biofuels (gCO_2 eq/MJ) [75, 72]

	Corn ethanol	Sugarcane ethanol	Soyabean biodisel	Rapeseed biodisel
Feedstock farming	30.8	22.5	34.2	57.5
Fertilizer production	10.1	3.8d	Not separated	Not separated
N_2O emissions in field	16.7	6.7e	20.1	Not separated
Farming	4.0	12.0	14.1	Not separated
Fuel production	31.0	2.6	9.6	15.2
Transport and distribution	4.5	1.8	1.9	1.9
Co-product credit	−13.7	−6.4	Not separated	−20.8 g
Total without credit	66.3	27.7 h	45.7	74.6
Total with credit	52.6	21.3	16.8	53.8

Partnership, intended for the development of an approved assessment methodology for the balances of greenhouse gases. Of no less importance is the development of an agreed approach to the assessment of a wider ecological and social influence of bioenergy crops in order to provide with transparency and compliance of the results within a wider range of systems. This can be done if strict requirements are put to picture completeness and accuracy during the calculation.

5 Biofuel Production Influence on the Land and Water Resources as Well as on Biodiversity

Intensification of systems for agricultural production of raw materials for biofuel and repurposing of the currently available and new croplands will have ecological consequences which extend beyond the scope of influence on the greenhouse gas emissions. The nature and severity of these consequences depend on such factors as the scale of production, kinds of raw materials, methods of cultivation and land use, location, and ways of further processing.

At the moment, there are not enough data on the impact which is directly connected with the intensified biofuel production, but the majority of problems in this field are similar to the problems observed in agricultural production:

- depletion and contamination of water resources;
- soil degradation and nutrient depletion;
- loss of natural and agricultural biodiversity.

5.1 Impact on Water

In many situations, it is the water shortage instead of land one that can be found to be the main limiting factor for the biofuel raw materials production [76, 77]. Currently, around 70% of fresh water in the world is spent on agricultural needs [78]. Many countries feel an increasing deficiency of water resources for agriculture as a result of an increase of competition with domestic and industrial uses. Besides, the load on already insufficient resources will increase further because of expected consequences of climatic changes, such as the reduction in the amount of precipitations and river flows in some of the main regions (including the Middle East, North Africa and South Asia).

At present, in the whole world the biofuel production uses approximately 100 km^3 (or 1%) of all the water absorbed by agricultural crops, as well as approximately 44 km^3 (or 2%) of all the water used for irrigation [79]. It is worth mentioning that water quantity and quality are the key factors influencing ecological sustainability in biofuel production [70, 80].

In order to achieve industrial capacities during the cultivation of many crops currently used for biofuel production, such as sugarcane, oil palm and maize, relatively much water is needed, thus, such crops are more suitable for tropical regions with a high level of precipitations or for the places where artificial irrigation is possible.

Even for perennial plants, such as jatropha and pongamia, which can be cultivated in semi-arid regions on marginal or degraded lands, irrigation may become necessary during a dry and hot summer. Moreover, the process of raw materials conversion to biofuel can require a lot of water. However, it is the irrigated production of the main kinds of raw materials for biofuel that will make the greatest impact on the local balance of water resources. Many regions producing sugar on the irrigated lands in South Africa and East Africa, as well as in the north-east of Brazil, have practically depleted the hydrological capabilities of the river basins in use. This is the case of the river basins of Awash, Limpopo, Maputo, Nile and San Francisco.

Even if the potential for expansion of the irrigated areas can seem high in some regions due to the availability of water and land resources, the actual capacities of biofuel production growth in the irrigated conditions on the available or new irrigated lands are limited with the demands to infrastructure, water supply provision, and the existing land-tenure systems which can be non-compliant with the systems of industrial production.

The highest potential for expansion is present only in Latin America and in Africa, to the south from Sahara. However, judging by predictions, in the last-mentioned region the level of water consumption for irrigation, which used to be low so far, will gradually increase.

The expansion of the production of agricultural crops for biofuel will influence both the quality and the quantity of water. The conversion of pasture lands and forests to maize fields, for example, can enhance such problems as soil erosion, sedimentation and drain of excessive nutritional chemicals (nitrogenous and phosphatic ones) to the surface waters, as well as infiltration of the surplus of applied fertilizers to the underground waters. An excess of nitrogen in the Mississippi river system is the main reason of emergence of the oxygen-free “dead area” in the Gulf of Mexico where a lot of species of marine fauna cannot exist.

An important water quality issue related to the increase in the cultivation of bioenergy crops is the contamination with nutritional chemicals as a result of surface runoff and infiltration to the subsoil waters. The paper [81] states that after the substitution of maize-soybean crop succession with constant maize planting for the production of ethanol in the United States of America the problems will escalate due to the wider application of nitrogenous fertilizers and their drain.

What concerns the stages of distribution and storage, then, as ethanol and biodiesel decompose under the influence of microorganisms, they have less negative impact on the soil and water resources during the drain and spillage than the fossil fuel.

In Brazil, where sugarcane for ethanol production is cultivated mainly under the conditions of rain watering, water availability is not a limiting factor, however a bigger concern is triggered by water contamination related to the application of fertilizers and agrochemicals, soil erosion, sugarcane washing and other stages of ethanol production process [82]. A big part of factory drains water (vinasse) is used for irrigation and fertilization of sugarcane plantations, reducing in such a way the water demand and the risk of eutrophication.

Pesticides and other chemicals can get washed away to water bodies and deteriorate water quality. The need in fertilizers and pesticides differs significantly for maize, soybean and other biofuel raw materials. Among the main kinds of biofuel raw materials, the highest application rate of fertilizers and pesticides per hectare is peculiar for maize. The production of biofuel from soybean and other, not much fertilized and quite diverse, biomass in prairie regions demands per unit of produced energy only a small portion of nitrogen, phosphorus and pesticides used for the production of biofuel from maize and, correspondingly, does not make such a negative impact on water quality [83].

At the same time, the above mentioned problems related to the quantity and quality of water for bioenergy crops production can be controlled by way of a proper selection of agricultural crop species and optimal management (for example, of harvest gathering speed, irrigation, corresponding plant food and filter strip) which raises the possibility of balancing bioenergy production and water resources conservation [84]. Applying the modern technologies of waste water treatment, organic impurities and waste can be effectively fought with. Fermentation systems can decrease the biological oxygen demand in the waste waters more than by 90%, that is why water can be re-used in the production process, while methane can be absorbed by a purification system and used for electrical power generation.

5.2 *Impact on Soil*

A negative impact on the soil is made both by changes in the land use structure and the intensification of agricultural production on the existing croplands, but such impact is dependent to a significant extent on the agricultural technologies for all the crops with no exceptions. Unacceptable techniques of agricultural crop cultivation can reduce the content of organic substances in the soil and increase its erosion due to the removal of a constant soil mantle.

Soil erosion is a very common and serious problem which is an important issue in the production of bioenergy crops as erosion deteriorates soil quality and hereby decreases the production capacity of natural and agricultural ecosystems. Soil erosion can be caused by three main ways: expansion of maize areas, elimination of plant remains, and change of land use. The expansion of maize areas due to the increase of demand for ethanol can cause serious adverse consequences for soil management [76].

The elimination of plant remains can deteriorate soil nutrient content and increase greenhouse gas emission due to the loss of soil carbon. On the other hand, conservation tillage, crop successions and other improved farming methods under favourable conditions can reduce the negative impact or even improve the state of environment along with the expansion of production of biofuel raw materials [85].

Cultivation of perennial plants, such as palm, fast-growing coppice crops, sugarcane or millet, instead of annual crops, can improve soil condition due to the boost of soil mantle and the increase of organic carbon level. If, in addition to this, tillage treatment is refused from and a lesser amount of fertilizers and pesticides is applied, then a positive influence on the biodiversity can be achieved.

The kinds of raw materials differ from each other by the impact on soil, needs in nutrients and the necessary degree of soil preparation. In particular, the sugarcane makes less impact on soil than rapeseed, maize and other grain crops. The quality of soil is maintained due to the recirculation of nutrients contained in the waste of sugar plants and distilleries, but the expansion of bagasse usage as an energy source during ethanol production reduces the recirculation.

Extensive production systems require re-use of waste for nutrient recirculation provision and soil conservation; in case of herbaceous crops and maize, as a rule, only 25–33% of crop waste can be gathered without environmental damage [86]. Under the conditions of increased demand for energy leading to the creation of crop waste market and in the absence of a proper process organization, such waste is used for the production of different kinds of biofuel that can potentially have a harmful influence on the soil quality, especially on its organic composition.

It has been established in the paper [83] that soybean production for biodiesel fuel in the United States of America requires much less fertilizers and pesticides per unit of generated energy than maize processing. However, the authors of the research state that both kinds of raw materials require a bigger amount of applied resources and the availability of higher-quality lands in comparison with the second-generation raw materials like millet, woody plants or different combinations of meadow grasses and graminaceous plants.

Perennial lignocellulosic crops, such as eucalyptus, poplar, willow or grass plants, do not require such an intense processing and demand less fossil fuel to be used as an input resource; besides, they can be cultivated on poor lands, and thereupon the content of soil carbon and soil quality, as a rule, improve in the course of time.

5.3 Impact on Biodiversity

Biofuel production can make a certain positive impact on the natural and agricultural biodiversity, for example, due to the restoration of degraded lands; however, its influence is mainly negative, for instance, in the cases when natural landscapes are to be repurposed for the production of energy crops or during marshland reclamation. In essence, during the expansion of croplands, natural biodiversity is under the threat of habitat loss, while agricultural biodiversity can suffer from a large-scale transition to monocropping which means the use of a narrow gene pool, and this leads to a reduction in the use of traditional breeds.

The first way which leads to biodiversity loss is the habitat disappearance resulting from repurposing of the lands, like, for instance, the use of forests or meadows for energy crop processing. It is known that many of the current-day energy crops are more suitable for tropics. This increases economic stimuli in the countries, which have favourable opportunities for biofuel production, to the conversion of natural ecosystems to plantations for the production of bioenergy raw materials (for example, oil palm) leading to a reduction of natural biodiversity in such regions.

Regardless of the fact that oil palm plantations do not need a big amount of fertilizers or pesticides even on poor soils, their expansion will lead to the reduction of tropical forest areas. In information coming from some countries it is stated that, as a result of land conversion to the production of raw materials for biofuel, a habitat loss is happening [87], but the data and analysis results which are necessary to make an assessment of the degree and consequences of such loss are still absent.

The paper [88] considers how a price increase on the goods which is caused by an increased demand for biofuel can influence land use and production intensification in Brazil. The authors have found out that the expansion of agricultural production due to the increase of prices can threaten the regions with a big diversity of bird species.

The second main way is the loss of agricultural biodiversity caused by the intensification of production on croplands which shows itself in genetic uniformity of crops. Most of the plantations of raw materials for biofuel are used for the cultivation of a crop of one kind. The concerns are voiced for a low level of genetic diversity of grass plants used as raw materials, such as sugarcane, which enhances the susceptibility of these crops to new pests and diseases.

For such a crop as jatropha, vice versa, an extremely high degree of genetic diversity is peculiar, a big part of which is not perfected, and this creates a wide range of genetic characteristics, reduces the commercial value of this crop.

What concerns the second-generation raw materials, it should be mentioned that some of the popularized kinds are classified as invasive, and this causes new problems in the sphere of their control and avoidance of unforeseen consequences. Moreover, a lot of ferments necessary for processing of such kinds are genetically modified with the aim of increasing the performance, and they must be handled very carefully, with the application of industrial technologies which ensure their isolation.

A positive impact on biodiversity was observed on degraded or marginal lands where new combinations of perennial species were implemented in order to restore functions of ecosystems and to increase biodiversity. Experimental data obtained on the investigated areas of degraded or derelict lands [89] indicate that low-cost, local perennial meadow plants do a wide range of ecosystem favours including the provision with habitats for wild fauna and flora, water filtration and carbon capture; they are characterized by high values of energy net increase (amount of energy released during combustion), by ability of a more significant reduction of greenhouse gas emissions, and less agricultural pollution in comparison with maize for ethanol production and soybean for biodiesel production; they increase their efficiency as the number of species grows.

Besides, the authors of this research have also found out that millet can produce a heavy yield on fertile soils, especially with the application of fertilizers and pesticides, but its yielding ability on poor soils is significantly lower than that of various local perennials.

5.4 Use of Marginal Lands

The marginal lands are usually areas degraded in a technogenic way, eroded or depleted in organic matter content, which are not profitable or convenient for agricultural crop cultivation for the production of food items, or naturally inappropriate territories like saline lands, marshes, wastelands, subacid or acid soils. Moreover, former or reclaimed industrial areas can also be marginal lands. And although these inappropriate lands may have a low fertility potential for producing heavy yields, they can still possess a high potential for producing the biomass for bioenergy production [90].

Marginal or degraded lands are quite often characterized by a shortage of water (which restraints the growth of plants and decreases the nutrient availability), as well as low fertility and high air temperatures. Typical problems of such areas are: degradation of vegetation mantle, water and wind erosion, salinization, soil compaction and soil crust formation, as well as depletion of nutrient stock. In some places, soil pollution, degleyfication, alkalization and bogging can happen as well.

Biofuel crops that are capable of sustaining the conditions in which food crops do not survive allow to use for cultivation the land which is currently providing with minor economic benefits [91].

Possible "candidates" for such a role are: cassava, castor-oil plant, sweet sorghum, jatropha and pongamia, as well as drought-resistant tree crops, such as eucalyptus. However, it is important to mention that quite often marginal lands provide with sources of the means of existence for low-income village dwellers and, in many cases, women. It will depend on the nature and reliability of the poor population's land title if they are going to gain or lose from the implementation of biofuel production on marginal lands.

Quite often one can hear statements that there are considerable areas of marginal lands which could be brought to use in biofuel production, and this would smoothen the competition with food crops and provide the poor farmers with a new source of income.

Although such lands are less productive and tend to have higher risks, their use in the form of bioenergy plantations can give additional benefits like restoration of degraded vegetation, carbon capture and the provision with local ecological services. However, the issue of appropriateness of such lands for sustainable production of biofuel is underinvestigated in most of the countries.

Cultivation of any crops on marginal lands with a low moisture content and poor nutritive properties will cause a decrease in yielding ability.

Drought-resistant jatropha and sweet sorghum are not an exclusion, and in order to ensure commercially acceptable yielding ability levels, the plant and tree species should not be subject to stress exceeding certain limits; in fact, a favourable impact on such species will be made by an introduction of a moderate amount of additional resources.

Perfected crops can provide with a potential for development in a long-term perspective, but in order to guarantee yielding ability that will be economically significant, a sufficient amount of nutritive substances and water will be needed, as well as the proper regulation; this means that even durable crops cultivated on marginal lands will still compete to some extent with food crops for such resources as nutritive substances and water [92].

6 Sustainability Criteria and Compliance Therewith

Although numerous and diverse ecological consequences of bioenergy development, in fact, do not differ from the consequences of other farming methods, the question about the best way to assess them and consider in agricultural practice is still in the agenda.

Existing methods of assessment of environmental impact and long-term ecological consequences can be successfully used as a basis for the analysis of biophysical factors. There also exists an enormous amount of technical solutions based on the experience of agriculture development in recent years. Among new investigations in the bioenergy field are: basic analytical solutions in the domain of bioenergy, food security and analysis of bioenergy development consequences, work regarding a complex influence on environment, including acidification of soil, excessive application of fertilizers, biodiversity loss, air pollution and toxicity of pesticides [93], as well as the work dedicated to the criteria of social and ecological sustainability, including the boundaries of disafforestation, competition with food production, negative impact on biodiversity, soil erosion and nutrient depletion. Biofuel sector is characterized by the availability of a wide range of activity subjects with different interests. In combination with the sector's quick development, this led to the appearance of numerous initiatives directed at the provision of a sustainable development of bioenergy.

Sustainability criteria are developed to ensure biofuel and bioliquid production with the usage of ecologically sustainable methods and fostering the decrease of biofuel influence on the climate change. Obligatory criteria of sustainability for biofuel are outlined in the Directive on the promotion of the use of energy from renewable sources 2009/28/EC, directive as amended in year 2015, and the Directive on the quality of transport fuels 2009/30/EC;

- reduction of greenhouse gas emissions from the use of biofuels and bioliquids by at least 35% (50% starting from year 2012 and 60% from year 2018). Since January 1, 2017, this requirement has constituted 50%, while since January 1, 2018, it has been equal to 60%, correspondingly, for biofuels and bioliquids produced at installations which have been put to operation since the beginning of year 2017;
- prohibition of the production of raw materials on the territory with a high value of biodiversity (a forest, a nature reserve, a pasture);
- prohibition of the production of raw materials on the areas under peat lands;
- prohibition of the production of raw materials on the areas which are significant carbon collectors;
- use of control system over information storage (mass balance systems) to track sustainable products.

The compliance with the above-mentioned sustainability criteria and their execution by the producers of biofuels and bioliquids are confirmed with the following:

- use or implementation of voluntary certification schemes recognized by the European Commission;
- by way of submitting the package of corresponding data to a responsible national body for check;
- concluding the agreements regarding sustainability conditions (two-, three-party ones) with third countries recognized by the European Commission.

It should be noted that the main requirements of sustainability are the requirements about the reduction of greenhouse gases during the cultivation of raw materials, biofuel production and use.

The raw materials which do not meet these sustainability criteria cannot be included to the implementation of aims concerning renewable energy sources, cannot get a financial support and will not have an appeal to EU fuel and energy companies. It is worth mentioning that at the moment the obtainment of subsidies is the main lever of influence over the production of biofuel: in case of non-execution of the approved rules of order by the producers, they lose a right to a subsidization of their costs.

The companies which are biofuel importers or biofuel sellers to the EU member states (“obliged companies”) are to report to a responsible body of EU member state that the biofuel they are supplying the market with meets the established sustainability criteria of EC Directive on the renewable energy sources. For this purpose, the obliged companies must use a certification procedure.

The certification is understood as the procedure with the help of which the body, which is established in the defined order (authorized), confirms documentarily the compliance of the products, quality control systems, environmental management systems, personnel safety management systems with the requirements set by the legislation. Thus, certification guarantees that biofuel is produced in a sustainable way and ensures the reliability of information using control on the part of the system or authority body.

EU member states and countries that are supplying European market with biofuel must provide with the regulatory framework for the companies to report on the compliance of biofuel or biofeedstock with EU sustainability criteria. Legislative acts must define which rules of reporting and certification are to be followed by the companies. EU member states can implement this by way of creating their own certification scheme or by way of approving voluntary certification schemes which already exist for the food market, forage market and biofuel. Certification schemes in the EU are approved by the European Commission. After the certification schemes are approved by the European Commission, they must be automatically approved by all EU member states [86].

7 Particularities of Using Biofuels and Their Mixtures

The biofuel for internal combustion engines is used both in the form of fuel mixtures and in its pure form. Fuel mixtures are the mixtures of traditional and alternative kinds of fuel in different percentage. The selection of the mixing technique is determined mainly by physical characteristics and further behaviour of biofuel components.

Mixtures with a low content of biofuels are regarded as compatible fuels, [94] at the same time mixtures with a higher concentration of biofuels can cause problems in fuel pipelines and affect the efficiency of fuel use and performance of transport vehicles.

Biodiesel can be mixed with a traditional diesel fuel or burnt in its pure form in the motors with ignition from compression. Its energy intensity constitutes 88–95% of diesel fuel; however, it improves the lubricating ability of traditional diesel fuel and increases the methane number ensuring general comparability of both kinds of fuel in the aspect of economical operation. A higher oxygen content in biodiesel fuel facilitates better fuel burning reducing the emissions of aerosol pollutants, carbon monoxide and hydrocarbons. Like in the case with ethanol, biodiesel contains just a negligible quantity of sulfur, thereby reducing motor vehicle emissions of sulfur oxides.

During diesel motor conversion to operation on biodiesel fuel, different physical and mechanical properties of fuels need to be taken into account. This property difference shows itself in the change of power and torque, change of fuel consumption, change of qualitative and quantitative characteristics of harmful substances in exhaust gases, change of motor thermal behaviour, etc.

One of the main problems occurring during motor operation on biodiesel fuel is a high viscosity of the fuel. It influences the production capacity of a fuel feed system, namely the functioning of a fuel pump, fuel filters, and the formation of fuel-air mixture [95]. Investigations have shown that biodiesel fuel heating improves the characteristics related to a high viscosity, allows to use biodiesel fuel in the cold time of year and to provide with the same viscosity characteristics regardless of temperature differences.

It should be mentioned that the use of vegetable oils in their pure form for diesels is held back by an increased carbon deposition, i.e. coke deposition on injector spray nozzles and other details that make up a combustion chamber.

The increase in carbon deposition is fostered by the availability of resinous substances in vegetable oils, i.e. their increased coking ability. In order to decrease the coking ability of vegetable fuels, a purification from resinous substances is necessary, as well as the use of mixtures of vegetable oils and diesel fuel.

What concerns the biodiesel, there are the following factors limiting mixing percentages or grades in fossil fuel:

- biodiesel has a shorter storage time than an ordinary fossil diesel oil, that is why it is needed to avoid its deterioration during storage and mixing;
- biofuel is usually mixed right before its transfer to a filling station, in which case, the fuel must be used within a limited time;
- in cold weather, biofuel can form gel and wax crystals, which can be a reason of fuel filter clogging and influence the reliability of transport vehicle performance.

Ethanol can be mixed with gasoline or burnt in its pure form in slightly modified motors with spark ignition. A litre of ethanol contains approximately 66% of the energy provided by a litre of gasoline, but at the same time has a higher-octane number and, in case of mixing with gasoline for the use in transport vehicles, this increases its performance values. Besides, it improves fuel burning in cars and thereby reduces the emissions of carbon monoxide, unburnt hydrocarbons and cancerogenes. A perspective application is its use as additives to commercial gasolines and amyl alcohol diesels, i.e. the waste during alcohol production. As of today, Brazil remains the only country in the world where 100% bioethanol is used as a motor fuel.

During the usage of ethyl alcohol (or its compounds) in motor vehicles in its pure form, a number of difficulties emerge which are connected with:

- worsening of motor start-up, with almost impossible start-ups at negative ambient temperatures, due to an increased (by a factor of 3.24) heat of alcohol evaporation compared to gasoline;
- unstable motor performance practically on all modes of operation in case of absent special heating of alcohol-air mixture;
- worsening of ecological performance characteristics in the case of motor operation without mixture heating;
- increased aggressive influence of alcohol compounds on some details of motor supply system.

Therefore, the use of ethyl alcohol or alcohol compounds instead of gasoline requires an appropriate modification of systems and motor assembly units.

In case of bioethanol mixing, it should be noted that ethanol has a corrosive impact and also influences economic values of fuel use. The amount of ethanol, mixed in the reservoir, is limited by a maximum quantity of oxygenates allowed by weight percent. Ethanol must not be conveyed through gasoline product pipelines; a separate system is needed for its transportation. Preliminarily mixed gasoline component, without ethanol, is usually fed through a pipeline, while ethanol is conveyed separately by road, railway or marine transport.

However, the particularity of ethanol as a mixture component is different from biodiesel fuel, as ethanol is used not only for the execution of regulatory functions. Ethanol is also used as an octane booster 80 replacing its other components of an octane booster.

The mixture grades used in standard vehicles are limited with a low biofuel content in order to avoid the deterioration of quality of motor and fuel system. The main reasons of this are: incompatibility with some diesel exhaust systems and motor oil dilution, filter clogging, erosion or compression, depending on the type (kinds) of biofuel.

Fuel use diversification by way of mixing requires accurate information for consumers. And vice versa, automobile motors and power-plants must be modified in order to work with higher content mixtures in a reliable way. However, this variant demands the continued availability of lower content mixtures to meet the demand for fuel, for older transport vehicles. Transport vehicles and filling stations must also be correspondingly equipped with simple means and labels to enable car filling with an appropriate fuel for the driver.

The interval of biofuel content regulation differs significantly for different EU countries (Table 6). The standardization of high-quality fuel containing persistent biocomponents is extremely important not only for the provision with a trouble-free motor operation at present, but also for future transport vehicles, as well as for assurance of effective work of the market.

It is worth remarking that greenhouse gas emission reduction and biofuel energy efficiency are not happening simultaneously. In general terms and taking into account the exclusions, the use of alternative motor fuels, including biofuel, allows to reduce

Table 6 Examples of biofuel brands for EU member countries [46]

Mixing grade	EU member countries	Short description
E10	France, Germany, Finland	Up to 10% of ethanol in gasoline
E85	Austria, Germany, France, Italy, The Netherlands, Sweden	Up to 85% of ethanol in gasoline
B7	France	Up 7% FAME in diesel fuel
B20	Poland	For captive fleets
B30	France	For captive fleets
B100	Germany	For adapted motors

greenhouse gas emissions. However, biofuels have a less energy content than fossil fuel.

As an example from Table 7 below, ethanol is characterized by a less heat content than gasoline (26.8 MJ/kg vs. 43.2 MJ/kg), that is why biofuels should be used based on energy content/ density instead of volume units. The results of investigations specified in Table 7 show that the use of biomass-based transport fuels can lead to the reduction of CO_2 emission levels, but at the same time in this case there is no net energy saving due to a lower calorific value of biofuel compared to fossil fuel.

All traditional or alternative kinds of fuel are the result of the production/distribution processes of energy consumption and emissions. Therefore, it is also necessary to consider stages and processes needed for the production of traditional and alternative kinds of fuel, their energy efficiency and greenhouse gas emissions per unit of energy.

According to the research [96], the improvement efficiency for gasoline motors is, first of all, related to specific features of fuel, such as higher-octane number of biofuels. During the use of high content mixtures (>50%), 15% efficiency increase is possible; an efficiency increases up to 10% is also possible in the case of 20%

Table 7 Fuel properties [46]

Fuel	Density	LHV	Emission factor	Emission factor
Unit	kg/m^3	(MJ/kg)	g CO_2/MJ	kg CO_2/kg
Liquid hydrocarbons				
Petrol 2000	0.75	42.9	74.4	3.19
Petrol 2010	0.745	43.2	73.4	3.17
Diesel 2000	0.835	43	73.5	3.16
Naphtha (HT)	0.72	43.7	71.2	3.11
FT Diesel	0.78	44	70.8	3.12
Oxygenates				
Methanol	0.793	19.9	69.1	1.38
Ethanol	0.794	26.8	71.4	1.91
MTBE	0.745	35.1	71.2	2.5
ETBE	0.75	36.3	71.3	2.59
DME	0.67	28.4	67.3	1.91
FAME	0.89	36.8	76.2	2.81
Gases				
Comp. Hydrogen		120.1	0	0
Liquid hydrogen		120.1	0	0
CNG (EU mix)		45.1	56.2	2.54
HVO (Nesté)	0.78	44		
LPG			65.7	3.02

ethanol mixture use. It means that actual decrease of fossil fuel can be higher than the portion of biofuel.

8 Biofuel Use Impact on Human Health

The conducted investigations testify to a direct interconnection of emissions of harmful substances with the growth of amount of diseases and an increase in people's premature death. Based on the data regarding the cost of medical treatment of the diseases caused by emissions in the United States of America and in the European Union, value estimates of the influence of motor vehicles on human health were obtained. They reach up to 80–85% of the total environmental damage [97].

The enumeration of environmental damage allows to take a different view on the usage of different kinds of fuel on a motor transport including also that in the conditions of densely populated cities, where the task of emission reduction demands the most focused attention.

An unfavourable ecological situation resulting from the negative consequences of motor transport functioning, complexified with the factors of outstripping development of the transport system and an increase in the motor vehicle fleet, leads to the necessity of taking into consideration an ecological constituent during the reasoning of innovative solutions and selection of technologies.

Contrary to the greenhouse gases which get mixed in the atmosphere and influence the climate change on the global level, air quality contaminants influence the environment on local and regional scale. It is clear that the loss of health due to environmental degradation is significant and demands intervention. These interventions to environmental policy, in turn, can save money spent on health care.

The investigations that considered the final impact of biofuel are constantly revealing that corn ethanol does damage to human health as equal to gasoline or even higher (Fig. 13) [98, 99]. And vice versa, the same investigations showed that health-care expenditures related to cellulosic ethanol will likely be lower than those of corn ethanol and can be marginally better than gasoline expenditures.

The use of biofuel in transport vehicles causes emissions of pollutants during evaporation and combustion. The amount of these emissions depends on different factors including combustion technologies, control of emissions, temperature and content of biofuel in the mixtures with oil-based fuels. Reviews of literature have shown that in regards to oil-based fuels, the biofuel use, as a rule, reduces the emissions of some pollutants increasing the emissions of others [100].

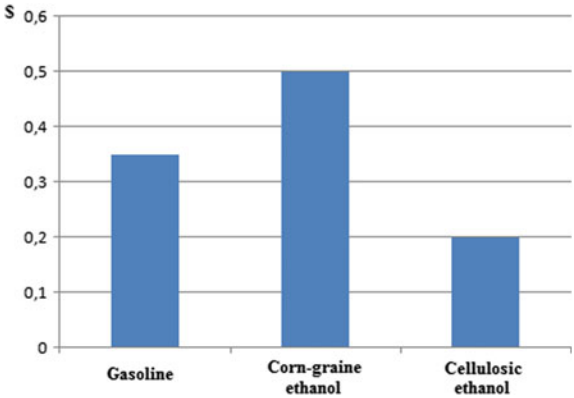


Fig. 13 Health-care expenditures (dollars per gallon of gasoline equivalent) related to the influence on air quality in the life cycle of gasoline, corn ethanol and cellulosic ethanol [98, 99]

9 Influence of Biofuel Use on the Reduction of Greenhouse Gas Emissions

9.1 Emissions from Biodiesel Use

The investigation of exhaust gas emissions in the case of biofuel use is extremely important for the assessment of their general influence on human health and environment. A biodiesel is a mixture of different fatty acid methyl esters, and its hydrocarbon content is different from fossil diesel fuel one. These differences in the chemical content influence a number of physical properties, which, in turn, can influence the exhaust gas emissions that differ from the emissions from traditional kinds of fuel.

Used as a transport vehicle fuel, biodiesel has some advantages regarding emissions and exhaust gases compared to the common fuels: diesel and gasoline. According to the data [101], in case of biodiesel use, the number of solid particles, carbon monoxide and unburnt hydrocarbons decreases, while fuel consumption and nitrogen oxide emissions increase (Table 8).

The advantages of biodiesel fuel use are especially significant because the carbon dioxide (CO_2) emitted during fuel burning is compensated by the fact that the plant crops, from which biodiesel is produced, consume CO_2. Besides, as a result of going

Table 8 Average change of mass emissions due to the use of biodiesel fuel in comparison with the use of a standard diesel fuel [101]

Biodiesel fuel	NO_x (%)	PM (%)	CO (%)	VOC (%)	SO_2 (%)
B20	+ 2.4	−8.9	−13.1	−17.9	−20
B100	+ 13.2	−55.3	−42.7	−63.2	−100

through different physical and chemical processes, biodiesel has a positive influence on diesel motor emissions [102–104].

Most of investigations of biodiesel use impact are based on the measurements of emissions for heavy vehicles and motors. Only in some works there were a few investigations carried out for diesel motor cars [105, 106].

At the same time, the impact of biodiesel use on controlled pollutants is not unequivocal. Mainly, it depends on physical and chemical properties of biodiesel, mixing ratio, car/motor design and conditions of movement. As a rule, the impact of biodiesel fuel on the controlled pollutants grows as the biodiesel content in fuel increases, and reaches maximum values if pure biodiesel is used.

According to the data [34], the use of a pure (100%) HVO, compared with the use of EN 590 diesel fuel, led to the decrease in NO_x emissions by 16% and smoke by 23%.

The paper [107] presents a comparison of exhaust gases in case of 100% HVO (of NExB brand) use with EN 590 diesel fuel use. Hydrotreated vegetable oil (HVO) under the name of NExBTL is the diesel fuel of the second generation produced using the technology of conversion of vegetable oils to paraffins. It does not contain sulfur, oxygen, nitrogen or aromatic substances. Cetane number of NExBTL vegetable oil is very high (~90). The investigations were conducted with the use of two heavy diesel engines and two city buses. The research data (Table 9) show a significant decrease in contaminating substances in the case where a pure hydrotreated vegetable oil of NExB brand was used.

As a result of investigation of motor parameters during its operation on the biodiesel fuel made of soybean oil and on a common diesel fuel, the reduction of CO and CH emissions and the increase in nitrogen oxide emission have been found out (Table 10) [108]. The comparison of two biodiesel fuels made of soybean oil and sunflower oil showed their significant difference in some parameters. In sunflower oil biofuel, the presence of methanol (0.5%) and glycerin was found out, i.e. the quality of this fuel did not correspond to the established standards. During motor operation on a mixture of sunflower oil and diesel fuel in the ratio of 30:70, a significant increase of exhaust gas temperature was observed, as well as an increase of NO content in exhaust gases.

It is known that physical and chemical properties of pure vegetable oils, which are different from those of diesel fuel, cause some difficulties during their use for diesel motor energy supply. One of the main physical and chemical parameters of fuel, which has an influence on the injection process and, therefore, an indirect influence on the combustion process, is viscosity. The irregularities in the combustion

Table 9 Effect of the use of 100% HVO compared with EN 590 diesel fuel [107]

Emissions	Units	Parameter values
Solid particles	%	−28 to −46
NO_x	%	−7 to −14
HC	%	−5 to − 78
CO	%	−5 to −48

Table 10 Parameters of motor operation on diesel and biodiesel fuel [108]

Parameter	Units	Diesel fuel	Bio EST
Effective specific consumption	g/(kW·h)	349	337
Effective efficiency	%	24.2	25
Temperature of gases	°C	289	289
Excess air factor		2.1	2.16
NO_x	ppm	693	841
CO	%	0.036	0.021
CH	%	0.24	0.0323

process cause an increase of emissions of exhaust gas toxic substances, mainly NO_x nitrogen oxides, and the level of solid particles (PM). The authors [11] conducted the research of the use of fuels made of pure rapeseed oil and canola oil, and, in addition to them, 10% n-hexane. It was noted that the addition of 10% n-hexane to canola oil and rapeseed oil improved physical and chemical properties of the fuels. The investigations were conducted with the use of pure oils and with addition of n-hexane in the amount of 10%, for the operation of motors without load and in real road conditions. It is noted that NO_x emissions, both for pure oils and oils with an additive, were higher in comparison with diesel fuel in case of motor operation without load in static conditions and also for motor operation in real conditions. CO_2 emissions for pure oils were higher in comparison with diesel fuel both for motor operation without load in static conditions and for motor operation in real conditions. At the same time, for the mixtures of oils with n-hexane, CO_2 emissions decreased to 11% value in real conditions.

Therefore, it has been found out that 10% additions of n-hexane improve physical and chemical properties of pure vegetable oils of canola and rapeseed and allow to use them in real road conditions of transport vehicle movement. At the same time, further investigations are necessary for improving environmental performance of obtained fuels.

The authors [108] made an analysis of the efficiency of oil fuel and biofuel use in multi-purpose diesels in full life cycle (including the phases of biofeedstock cultivation, biofuel obtainment and its combustion in the motor). It is shown that the use of biodiesel fuel in comparison with oil diesel fuel in the full life cycle allows to: reduce the consumption of non-renewable natural resources by 55–65%; reduce the emissions of greenhouse gases by a factor of 3.5–4.6; reduce the environmental damage by 15–16%; reduce the expenditures, taking into account environmental damage, by 40%. At the same time, the use of biodiesel fuel is connected with the increase of energy consumption in the full life cycle by 10–20% if compared with diesel fuel.

9.2 Emissions from Bioethanol Use

According to numerous research works, the level of bioethanol use, both as a mixture with gasoline and in its pure form, increases [6, 42, 86]. Thereby, quite step-ahead is the use of ethyl tert-butyl ether ETBE, which is obtained due to bioethanol mixing with isobutylene, going through a chemical reaction when heated over catalyst [109, 110]. An advantage of ETBE is that its usage overcomes many historic obstacles to a wider ethanol use, such as influence on gasoline volatility increase and non-compatibility with oil pipelines. At present, ETBE is used as an additive in several European countries, including France, the Netherlands, Germany, Spain and Belgium, and starting from year 2010 Japan also began using automobile fuels with a bio-ETBE additive in amount of 7% [111, 112].

Bioethanol can be used as a fuel in different ways:

- as a mixture with gasoline (from 5 to 85%). As 5% mixture, it can be used in all gasoline motors. As a low-percentage alcohol-gasoline blend (ethanol also constitutes 10% of E10 known as "gasohol"), ethanol can also be used with or without a little modification of motor. However, higher content mixtures E85 require corresponding modifications.
- as a direct substitution of gasoline in the cars with appropriately modified motors;
- as a mixture with diesel in diesel motors, also known as "diesel" fuel mixtures;
- as a mixture with biodiesel in diesel motors, also known as "BE-diesel" fuel.

Thereby, a special attention is focused on the emissions of NO_x and solid particles, as these pollutants are connected with a big influence on human health. The investigations of the impact of specific kinds of fuel on NO_x emissions are especially relevant for the regions where a photochemical pollution happens.

One of the prime considerations for the usage of high content ethanol mixtures is the reduction of atmospheric pollutant emissions from the fuel. As ethanol is an "oxygenate", and a higher oxygen-fuel mixture is injected, in this case an improvement of combustion efficiency is expected. However, the real picture is much more complicated than the mentioned reason.

The investigations [113, 114] are indicative of considerable fluctuations of NO_x emissions during the use of E10 bioethanol mixtures: starting from significant improvements with emission reductions to 67% and ending with significant deteriorations, with emission increase to 79%. The research results showed that in some cases E10 mixtures caused higher NO_x emissions if compared with a pure gasoline, in other ones confounded results were obtained, while in some others no differences were found out or emissions were lower. Thus, after comparing the results of investigations with the use of E10 mixtures, no consistent pattern was found.

According to authors' data [115], in case of E20 use in motor cars the average increase of NO_x emissions constitutes approximately 25%, the results of which vary from −17 to +79%.

Contrary to those concerning diesel motors, the values of gasoline motor emissions are related to the operation of a three-way catalyst. In particular, for NO_x, if oxygen content in ethanol is not appropriately compensated by the motor, this will lead to the depletion of exhaust gases, which completely suppress the efficiency of catalyst performance, and this causes higher NO_x emissions.

As already mentioned, all kinds of fuel on the market which are used for transportation purposes must contain some portion of renewable energy sources, and ethanol in gasoline is a step-ahead solution for achieving this aim. Except the decrease of dependency upon the fossil fuel, ethanol fosters the reduction of pollutant emissions to the air during combustion (i.e. of carbon monoxide and total hydrocarbons) and has a positive influence on greenhouse gas emissions. These considerations are based on numerous emission investigations conducted under standard conditions (20–30 °C).

But there is very little information about emissions for the cold environment. The research results [116] showed a higher level of emissions at −7 °C than at 22 °C regardless of ethanol content in the fuel mixture. These results lead to the conclusion that for the adaptation of transport vehicles to alternative fuel characteristics, new technical devices, such as aftertreatment systems and block heaters, are needed at low temperatures.

Most of investigations assessing uncontrolled emissions are indicative of the emissions of benzene, toluene, ethylbenzene and aldehydes which are not proportionally dependent upon the mixing ratio [117]. Different ratios of ethanol and gasoline influence the emissions of vapours through different mechanisms.

The mixing of ethanol with gasoline to approximately 40–50% (E40–E50) leads to vapour pressure increase. This can cause an increase in evaporative emissions. The results of research regarding the influence of gasoline vapour pressure and ethanol content on emissions from modern European passenger cars confirm that vapour pressure is a key factor for emissions [118].

In general, fuel vapour pressure increase, which exceeds a certain limit, can cause an increase in evaporative emissions due to an enhanced mode of fuel vapour generation. Known as a mixing effect, the mixing of two different gasolines in the tanks of a transport vehicle leads to a general increase of gasoline vapour pressure.

Ethanol can also influence the emissions with the help of the mechanisms which are different from the increased vapour pressure of ethanol/gasoline mixtures. It is known that ethanol increases the speed of fuel penetration through elastomeric materials (rubber and plastic details) which make up a fuel system. The results of a large-scale research of fuel penetration showed that the emissions of hydrocarbons, not included to ethanol content, generally increased during the test of ethanol-containing fuels.

9.3 Emissions by Way of Evaporation

Emissions by way of evaporation from a transport vehicle can be defined as all volatile organic compounds (VOCs) emitted by the transport vehicle itself and not coming from the process of fuel burning.

One of the main problems related to the usage of gasoline/ethanol mixtures is a possible increase of emissions by way of evaporation from transport vehicles. For motor vehicles with gasoline motors, most of the evaporative emissions happen due to the loss of hydrocarbons from a fuel system.

More specifically, the main contributions to emissions by way of evaporation come from fuel evaporation from the reservoir and fuel penetration through fuel hoses, fuel tank, connectors, etc. [119]. Volatile organic compounds can also come from the materials used in transport vehicle manufacturing, such as plastics and interior furnishing materials, or from other system fluids (for example, windshield detergent). However, these emissions are usually very low in modern cars and they are by no means dependent on the fuel quality.

Ethanol has a significant influence on both exhaust gas emissions and gasoline emissions of motor cars when added to fuel, even at a low level (5%). Due to oxygen content in ethanol, some emissions of exhaust gases can be a bit lower, but some other uncontrolled pollutants (e.g. acetaldehydes) can increase. An increase in emissions due to ethanol evaporation is conditional upon a combination of factors:

- an increased vapour pressure of gasoline/ethanol mixtures;
- an increased penetration of fuel through plastic and rubber components of a fuel system;
- a mixing effect;
- increased emissions of filling devices.

Evaporative emissions are in connection with a serious impact on human health and environment. That is why, a more effective control over the emissions from evaporation is necessary for the whole lifetime of transport vehicles. Evaporative emissions must be controlled in a more effective way during real motion conditions and not only in laboratory conditions. There is an evidence of the fact that, in many cases, evaporative emission control systems are only developed for the purpose of passing the type approval tests according to a legislative procedure. A more effective control during the whole lifetime of transport vehicle also expects an improved life duration of evaporative emission management system.

10 Battery Electric Vehicles

Transport vehicles with gasoline and diesel internal combustion engines have already reached the peak of their development, that is why for further progress in the car field conceptually new power sources for cars are needed. A lot of scientists and developers of transport vehicles are striving to increase economic and environmental performance values of transport vehicles [120, 121]. The recent international car motor shows confirm this direction and are held under “green car” slogan demonstrating more and more electric car models. This is promoted both by consumers’ interest to eco-friendly means of transport and state-run programs of developed countries stimulating this demand.

Aiming at comparing the influence of biofuel on greenhouse gas emissions and competing “green” technologies, it is also worth taking into consideration the reduction of greenhouse gas emissions from a battery electric vehicle.

Electric vehicle batteries do not emit exhaust gases, but greenhouse gas emissions happen at the power plants producing electric energy. Thus, in this case, the emissions depend on the conditions of electric energy generation.

As a rule, gross electric energy output is an “electric energy mix” (for example, 30% of nuclear one, 25% of coal one, 16% of renewable one, etc.). “Electric energy mix” changes a lot depending on the time and geography of the region. Authors [46] report that in order to produce a unit of electric energy, kWh (in the conditions of European Union), the emissions of greenhouse gases constitute 540 g CO_2/eq/kWh. Vehicle batteries can use electric energy with different efficiency. According to the data [122], the efficiency of an electric-battery car on C-class motor car market constitutes 14.5 kWh/100 km.

It is known that different kinds of biofuel are significantly different in greenhouse gas balance if compared with fossil fuels, depending on the method of raw materials production and the fuel manufacturing technology. An important thing is the analysis of balance of all greenhouse gas emissions during all the stages of biofuel production and use. Table 11 presents the data on the analysis of alternative fuel influence on CO_2 emissions: without consideration of a full life cycle and with consideration of a full life cycle (WTW + ILUC) based on energy mixes.

Table 11 Volumes of CO_2 emissions without consideration (WTW) and with consideration of a full life cycle (WTW + ILUC) for different kinds of fuels [46]

Kind of fuels	Units	Average emission volumes WTW	Average emission volumes WTW + ILUC
Ethanol compared with gasoline			
2010 DISI petrol	gCO_2eq/km	178	
Wheat ethanol	gCO_2eq/km	137	162
Brazil sugarcane ethanol	gCO_2eq/km	51	77
Sugar-beet ethanol	gCO_2eq/km	58.6	85
Wheat straw ethanol	gCO_2eq/km	19	27
Corn ethanol	gCO_2eq/km	151	177
Biodiesel compared with diesel			
Common diesel	gCO_2eq/km	145	
Rapeseed biodiesel	gCO_2eq/km	93	182
Sunflower biodiesel	gCO_2eq/km	76	165
Soybean biodiesel	gCO_2eq/km	91	180
Palm oil biodiesel	gCO_2eq/km	79.6	169
Battery electric vehicle			
EU electric mix + battery electric vehicle	gCO_2eq/km	78	N/A

Based on the data from Table 11, one can make a conclusion that vehicle electric batteries offer better greenhouse gas saving than fossil fuels and most of the biofuels if the emissions of a full fuel life cycle are included. Thereby, the best greenhouse gas saving is achieved when gasoline is replaced with ethanol produced from wheat straw and sugar crops, while biodiesels from food crops offer savings in greenhouse gases only in the case when emissions of a full fuel life cycle are neglected. As electric vehicles save more greenhouse gases than the motors working on gasoline and diesel fuels, even with the existing (year 2009) mix of electric energy and emissions in the EU, then the increase of renewable sources in the general "electric energy mix" will be even more favourable.

One of the kinds of renewable sources for electric energy generation is a torrefied biomass [1]. The process of torrefaction involves heating of starting raw materials under atmospheric conditions and in the absence of oxygen up to 200–300 °C temperature, and keeping at this temperature during a set time. A torrefied biomass has consumer properties which are close to those of bituminous coal (Table 12).

Thus, its use for co-combustion with bituminous coal in order to generate electric energy can reduce significantly the use of fossil fuel, CO_2 emissions and, at the same time, stimulate the expansion of opportunities of using different biomass waste, which will also allow to increase the level of environmental safety.

Table 12 Comparative analysis of torrefied biomass and coal [123]

Characteristics	Unit	Torrefied mass	Fossil coal
Moisture	%	2–5	10–20
Lower heating value	MJ/kg	20–24	23–28
Output of volatile substances	% db	55–65	15–30
Fixed carbon	%	28–35	50–55
Bulk density	kg/l	0.75–0.85	0.8–0.95
Energy volumetric density	GJ/m^3	15.0–18.7	18.4–23.8
Ash content	% db	<3	10–40
Hygroscopicity		Low	Low
Grinding requirements		Ordinary	Ordinary
Biological degradation		N/A	N/A
Dust content		Allowable	Allowable

11 Carbon-Neutral Synthetic Fuels

Carbon-neutral synthetic fuels (CNSF) can offer sustainable alternatives to oil fuels, which dominate in the transport sector at the moment, and solve the problems of fuel mix de-carbonization. CNSF can be divided to synthetic biofuel produced from lignocellulosic raw materials due to gasification (Fig. 14) and "electric fuel" produced from carbon dioxide and water by way of electrolysis (Fig. 15) [119]. The main products of synthetic biofuel production are: hydrogen, synthetic natural gas, methanol, dimethyl ether, gasoline and diesel.

Synthetic hydrocarbon fuels can be used as perfect substitutes in their pure form or in any mixture ratios, in contrast with the first-generation biofuels. The advantage of such fuels is the fact that their use does not require an upgrade of transport vehicles or an erection of a new infrastructure and enables a smooth transition to alternative kinds of fuel without any obstacles.

Synthetic hydrocarbon fuels are increasingly frequently offered as a step-ahead solution for transport sector de-carbonization achievement, as they can be used in internal combustion engines and, contrary to the majority of biofuel types, they make a little impact on the land use. Such kinds of fuels could facilitate de-carbonization and be used as approximately 100 EJ/year in year 2050 [124].

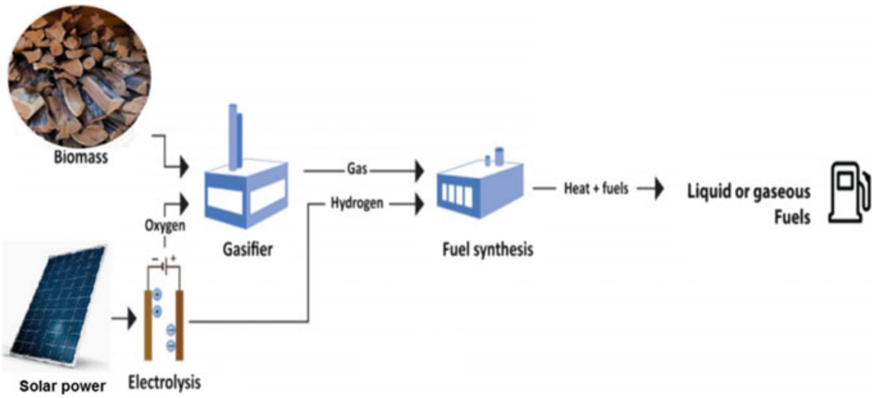
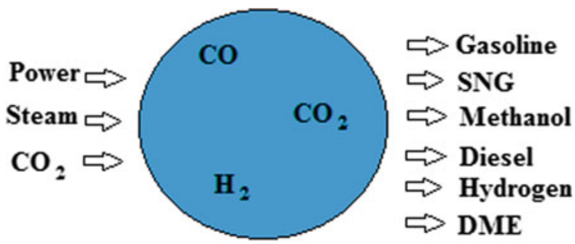


Fig. 14 Bioelectric fuel production chart

Fig. 15 Electric fuel production chart



At present, existing manufacturers of electric fuels are of pilot nature. An exception is Carbon Recycling International (CRI) company producing methanol (trademarked as Vulcanol) from renewable raw materials and, in such a way, obtaining fuel with a low carbon content and raw materials for synthetic materials [124, 125].

According to European fuel standard, methanol is allowed to be mixed with gasoline, in amount of 3%. Mixtures with 15% methanol content in gasoline are already in use in China and undergo tests in Australia, Italy, India and Israel. The Chinese authorities also facilitate the use of 100% methanol in motor vehicles, buses and trucks.

Methanol is used in biodiesel production, and also it can be used for the production of a synthetic fuel, such as gasoline or fuel ethers (DME, MTBE, OME, etc.), which are suitable both for diesel and gasoline motors.

In spite of numerous advantages of bioelectrofuels, the implementation of commercial projects is currently held back due to their high investment value.

12 Conclusions

1. Due to a significant growth in the demand for vehicles, greenhouse gas emissions are steadily increasing despite a substantial improvement in the effectiveness of environmental measures.
2. Although alternative fuels made from biomass have substantial potential for reducing pollutants in the long run, in our opinion, to improve the environmental situation, the technological potential for fossil fuels vehicles should be also better utilized.
3. Since the increase in the internal combustion engine efficiency is almost exhausted, fuel consumption is currently decreased by means of reducing the car weight and increasing the aerodynamic properties of the body.
4. Polymer composites and nanocomposites based on natural fillers with improved performance are a good alternative way to get lighter and more environmentally friendly materials for the automotive industry.
5. The environmental impact can be exerted at all stages of the production and processing of bioenergy raw materials, but the land use change and the production intensification come to the fore. Greenhouse gas emissions from the direct and indirect changes in land use and land cover are the variables with the greatest uncertainty and in many cases have the most substantial effect in the whole biofuels supply chain. Unless there are direct or indirect changes in land use or cover, biofuels have less greenhouse gas emissions over their lifecycle than oil-based fuels.
6. Greenhouse gas emissions from the use of biofuels depend on the type of cultivated raw materials, management methods used to grow them, any direct or indirect changes in land use, which may result from an increase in biofuel production, biomass collection and transportation, and technologies, used to convert biomass into fuel.

7. As the impact of expanded biofuel production on greenhouse gas emissions, land, water resources and biodiversity varies widely by country, type of biofuels, type of raw materials and production practices, there is an urgent need to coordinate the approaches to life cycle analysis, greenhouse gas balances and stability criteria.
8. Forage stocks, such as agricultural and forest plant residues and solid household wastes, do not cause any direct or indirect changes in land use or land cover. Thus, lignocellulosic biofuels made from these raw materials reduce greenhouse gas emissions faster, provided that land productivity and carbon storage in soil are maintained.
9. Perennial energy crops, such as grasses or trees, can diversify the production systems and contribute to the improvement of marginal or degraded lands.
10. Electric car batteries do not emit exhaust gases, but greenhouse gas emissions occur at power plants where electricity is generated. So, in this case, the emissions depend on the conditions of electricity generation.
11. Battery electric vehicles have a better greenhouse gas saving than most biofuels.
12. The use of carbon-neutral synthetic biofuels is a promising way to achieve the complete decarbonisation of the transport sector.

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Energy Efficiency and Ecological Impact of the Vehicles

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Abstract In this study, the energy characteristics of BEV and HEV were presented. Original experimental results for energy consumption are presented. The life cycle assessment of main types of ecological vehicles was done. As a base of comparison, the primary energy and CO_2 emissions of conventional gasoline vehicle was used. An area, concerning vehicles, which are more effective in economic and ecological aspects, at average Emission factor of EU-28, is defined. For a separate country, this area will be different, depend on value of its Emission factor of electricity production. The study gives the evidences for the hypothesis that electric vehicles do not generate emissions at the place, where it runs, can be used for resolving the local problems with air pollutions, but not global.

Keywords Energy characteristics of electric and hybrid vehicles · Life cycle assessment · Ecological vehicles · Emission factor · CO_2 emissions

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1 Energy Characteristics of Electric and Hybrid Vehicles

1.1 Energy Consumption of an Electric Vehicle

In search of solutions for the energy crisis of the last century [1–4] and the impact of transport on global warming [5–7], there has been an increasing interest in the production and putting into operation of a growing number of electric vehicles [8–12].

The testing of the vehicle energy characteristics is possible in real road conditions or in the laboratory, on the testing benches [13, 14]. Usually the result from road and laboratory tests have some difference.

The main characteristics concerning energy properties of a BEV are energy characteristic and power characteristic. First one is relation between specific energy consumption E in kWh/km and constant speed V in km/h. the power characteristic is relation between needed power P in kW and constant speed V, km/h.

An example of energy characteristic, in case of BEV with constant gear ratio in transmission (without gear changing), is shown on Fig. 1. At the low speed, energy consumption is higher. Then, there is an interval of speeds with low energy consumption. After that, at high speeds the energy consumption increases.

Usually the experimental result obtained on the road and in laboratory have differences. This can be seen on Fig. 2, which presents power characteristic of a converted electrical vehicle.

Fundamentals of electric vehicle energy consumption
The main purpose of energy, accumulated in the battery, is the supply electric motor

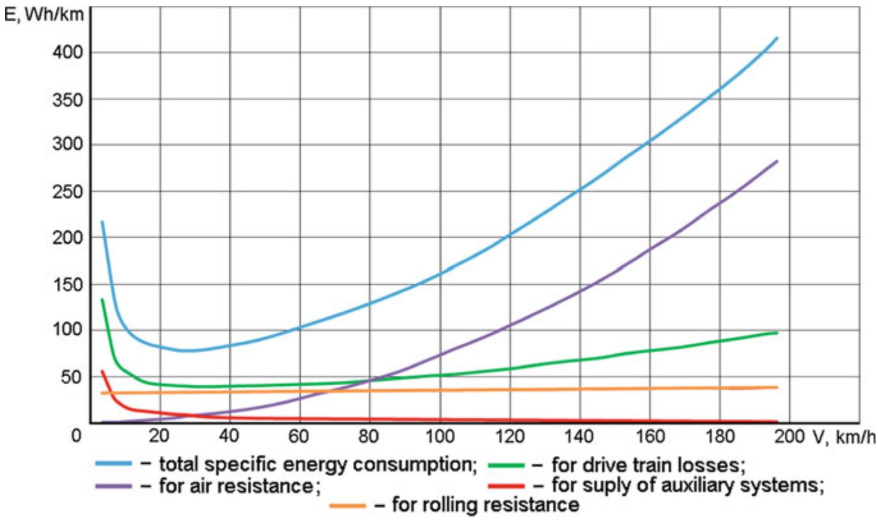


Fig. 1 Energy characteristic and distribution the total specific energy consumption of Tesla Roadster [140]

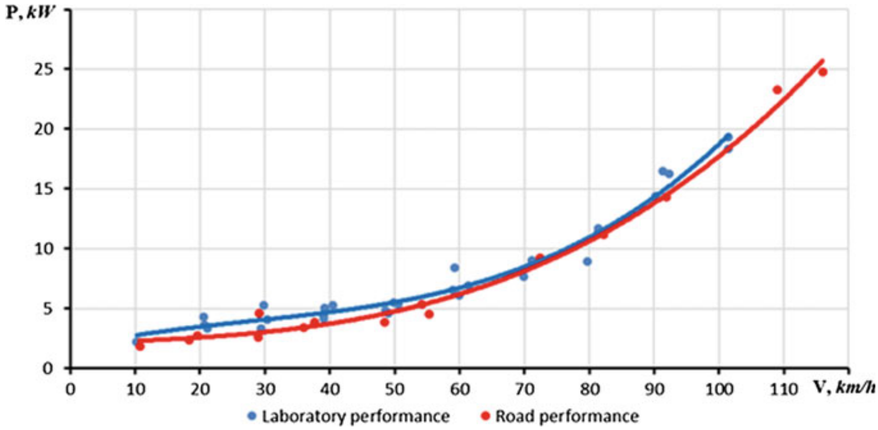


Fig. 2 Road and laboratory power characteristics [16, 19]

and to provide electric vehicle motion in different running conditions. In addition the battery has to provide also supply of auxiliary systems, which guarantee safety travel (as lights, horn, window cleaner etc.) and comfort (as air conditioning system, media etc.). During the travel, the value of specific energy consumption (in Wh/km or kWh/100 km) can be different. Depending on the skills and desires of the driver, energy consumption can arise over 2 times more than indicated in technical specification of the electric vehicle.

In general case, the specific energy consumption can be theoretically determined by following expression

$$E = \frac{100}{3.6\,\eta_M\,\eta_E}\left[\left(f_o + 5\times 10^{-7}V^2\right)G + k_B S\frac{V^2}{13}\right] + E_{AS},\ \text{kWh/100 km}, \quad (1)$$

where

f_o—is the rolling resistance coefficient at low speed;
V—the vehicle speed, km/h;
G—the vehicle weight, kN;
k_B—the coefficient of aerodynamic resistance, kN s^2/m^4;
S—the front area of the vehicle, m^2;
η_M—the efficiency coefficient of transmission;
η_E—the efficiency coefficient of the electric motor and power electronics;
E_{AS}—the specific energy consumption of auxiliary systems, kWh/100 km.

The coefficient k_B is calculated as

$$k_B = 0.5\times 10^{-3}\rho c_x,\ \text{kN}\,\text{s}^2/\text{m}^4, \quad (2)$$

where

ρ—is the air density, kg/m^3;
c_x—the drag coefficient.

The change of the air temperature t from +40 to −20 °C cause a change of it density from 1.127 to 1.395 kg/m^3 [15] and at high vehicle speed can increase the energy consumption over 10%. The value of the air density can be evaluated with good accuracy (deviation of not more than 0.5% at low temperature) using the relation

$$\rho = 2 \times 10^{-5}\, t - 0.0048t + 1.2926,\ \text{kg/m}^3. \tag{3}$$

Mechanical losses in the transmission vary in wide limits and they depend on the electric motor load. The efficiency coefficient η_M with good accuracy can be evaluated using the approach, proposed in [16]. The losses in electric motor and power electronics η_E also depend on working conditions and load. The product of both coefficients vary in 90–95%, but can decrease under 50% at some running conditions [17]. It is necessary to have the characteristics of elements of electric drive, not only at nominal load (which value is given in technical specifications), but also in particular load. Some of the researchers assign these two types of losses to so-called drive train losses [18].

Distribution of the total energy consumption of electric vehicle
An analysis of distribution of total used energy can be done on the base of an existing example. On Fig. 1 a real picture of the energy consumption of the electric vehicle model Tesla Roadster at different values of the speed is presented. The Air conditioning (AC) system does not work [18].

The ratio between different parts of total specific energy consumption changes with the increase of the vehicle speed. At low speed most significant is the part of energy consumption for drive train losses and supply of the auxiliary systems. Higher energy consumption at slow motion is caused by the low values of the efficiency coefficients η_M and η_E. At high speed, the part of energy, spent for air resistance becomes largest.

The energy spent for rolling resistance is changed in short limits, because of the small influence of the speed on the coefficient f_o.

In fact, during the motion the most variable can be the parts of energy spent for air resistance and supply of auxiliary systems. The last part depends on atmosphere conditions as rain, snow, wind etc.

The curves shown on Fig. 1 are well represented by the following regression models:

– total specific energy consumption

$$E = 4 \times 10^{-10} V^6 - 3 \times 10^{-7} V^5 + 7 \times 10^{-5} V^4 - 0.009 V^3 + 0.5715 V^2 - 16.313 V + 234.92,\ \text{Wh/km} \tag{4}$$

– specific energy consumption for drive train losses

$$E = 3 \times 10^{-10} V^6 - 2 \times 10^{-7} V^5 + 5 \times 10^{-5} V^4 - 0.0057 V^3 + 0.358 V^2 - 10.26 V + 139.27,\ \text{Wh/km} \quad (5)$$

– specific energy consumption for rolling resistance

$$E = 0.0297 V + 32.278,\ \text{Wh/km} \quad (6)$$

– specific energy consumption for air resistance

$$E = 1 \times 10^{-6} V^3 + 0.007 V^2 + 0.0035 V + 86.32,\ \text{Wh/km} \quad (7)$$

– specific energy consumption for supply of auxiliary systems

$$E = 121.1 V^{-0.794},\ \text{Wh/km}. \quad (8)$$

There are many models with gearbox in the transmission. In this case the energy characteristic shows consumption at every one gear (Fig. 3). Presence of the different gears gives possibility to choose more precise the working regime of the electric motor, and to cover wider range of speeds.

For laboratory test, concerning energy consumption, the driving cycles can be applied [13]. There are generally accepted driving cycle ECE 15 which is for conventional vehicles and also Special cycles for electric vehicles. Results obtained under first one cycle (Fig. 4) allow to compare energy consumption of the electric end conventional vehicles [13, 18].

The second cycle (Fig. 5) is specially developed for electric vehicles and can be used for comparative analysis only between these types of vehicles [13].

The energy consumption for some corporate electric vehicles [3, 13] are given in Table 1.

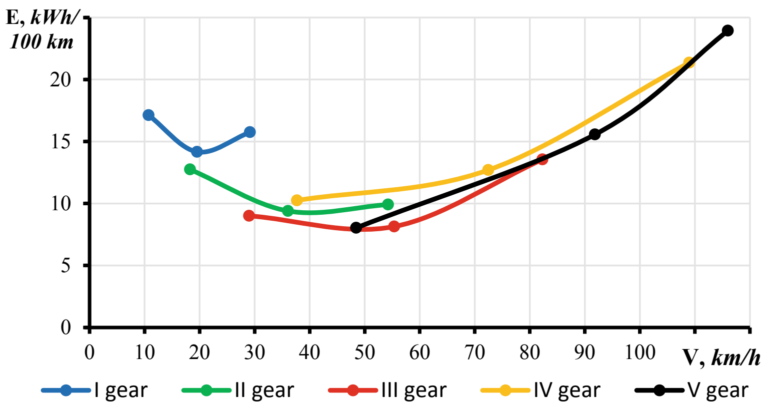


Fig. 3 Energy characteristic of a BEV on the road by gears [16]

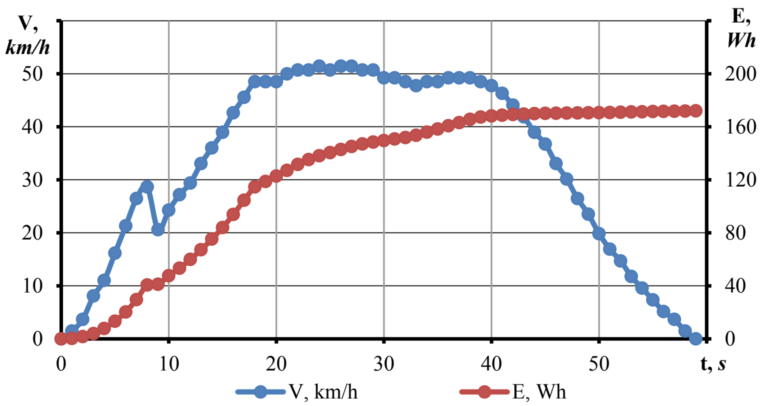


Fig. 4 Energy consumption during special cycle for electric vehicles [16]

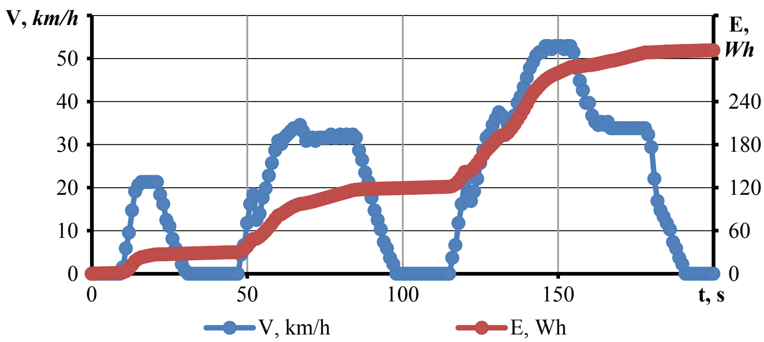


Fig. 5 Energy consumption during European driving cycle ECE-15 [16]

Table 1 Energy consumption in ECE-15 for electric vehicles with lithium rechargeable batteries

№	Electric vehicle	Mass, kg	Maximum power, kW	Energy consumption per cycle, kWh
1.	Mitsubishi MiEV	1370	47	1.96
2.	Renault ZE BE BOR	1881	44	2.71
3.	Mini E	1615	47	2.07
4.	TH!NK City	1547	30	2.20
5.	FIAT Phylla	970	27	1.42
6.	DuraCarQuicc!	1640	50	2.43
7.	TESLA Roadster	1385	184	1.99
8.	Protoscar LAMPO	1530	200	2.19

1.2 Fuel and Energy Consumption of a Hybrid Vehicle

One of the main environment pollution sources are vehicles [19–23]. In the last years, the alternative vehicle propulsion systems became the main priority for a lot of automotive companies and research teams. The basic objective of those propulsions [20, 24–27] is the achievement of energy independence from nonrenewable sources like liquid and gas fuels. One of the variants of vehicle propulsion, which is built-in a few vehicle models is hybrid system [25, 28, 29].

According to the information from the producers and a number of studies [21, 24, 25, 29–33] hybrid vehicle consumes less fuel and generates les air pollutions in comparison with a vehicle equipped with a gasoline or diesel engine during the city motion. Similar effect exists for inter-city conditions. That is one of the main advantages of hybrid vehicles because in city conditions, up to 50 km/h, the motion is realized using only electric energy from the battery.

In some studies [24–26, 28–30, 34] there are verifications that hybrid vehicle has advantages versus gasoline, even versus diesel vehicle especially in urban conditions. The fuel consumption in inter-city conditions are not well studied.

Estimate the energy or fuel consumption of a hybrid vehicle is very complex problem, because of computer control system and properties of transmission (CVT or not).

Fuel consumption at constant speed and energy characteristic of an example—Toyota Yaris Hybrid 1.5 HSD is presented on Fig. 6. At low constant speed, the energy consumption is a little higher (Fig. 6), which is a result of low values of the transmission and electric propulsion efficiency. Then the energy consumption slowly goes down. Up to 50 km/h fuel consumption is zero l/100 km, because for the motion, the vehicle use only electric energy (approximately 0.08–0.1 kWh/km) from the battery. At constant speed over 50 km/h, the fuel consumption is practically equal to that one of the conventional variant of the same vehicle. At high-speed conditions, the hybrid vehicle runs using only ICE. Obviously, it is not appropriate to make comparative analysis of different models hybrid vehicles only on the base

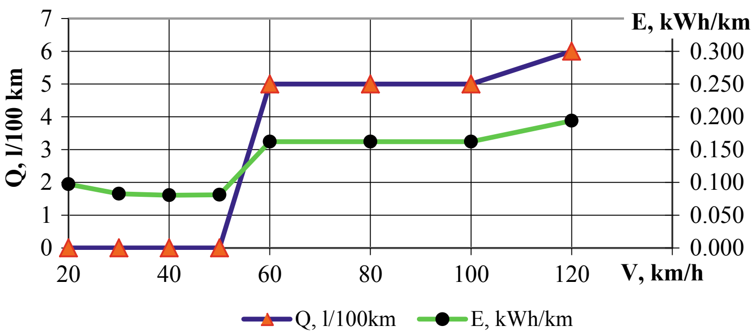


Fig. 6 Fuel consumption and energy characteristic of Toyota Yaris Hybrid 1.5 HSD [25]

of fuel consumption and energy characteristics. In real traffic, usage of the electric or ICE mode depends on many factors, including not only road conditions, speed, traffic density but also driver's skills, discharge level of the battery etc.

Our opinion is—an additional study of the fuel consumption of hybrid vehicle in urban and inter-city conditions is needed. That way a full picture concerning fuel and energy properties of the tested vehicle can be obtained.

Study of the fuel consumption of the hybrid vehicle in urban conditions
The experiments include series of tests in urban routs in Bulgarian town Ruse. Consumption on three typical urban routs [35] were investigated:

– Route 1 "Rail station—Danube bridge—Rail station" (Fig. 7);
– Route 2 "Rail station—River station—Rail station" (Fig. 8);
– Route 3 "Rail station—Druzhba 3—Rail station" (Fig. 9).

The first route has a predominant plane terrain and a distance of 15.3 km. The second one includes horizontal and also parts with longitudinal inclination. On this route the motion in one direction and return to start point are realized by passing through different streets, because of presence of one way streets. Distance of the second route is 4.6 km. The third route has a predominant hill terrain. The distance is 6.4 km.

Motion was realized in the traffic peak period—17–18 h. Every route was passed in two modes—without and with activated "ECO MODE" of the hybrid system. The

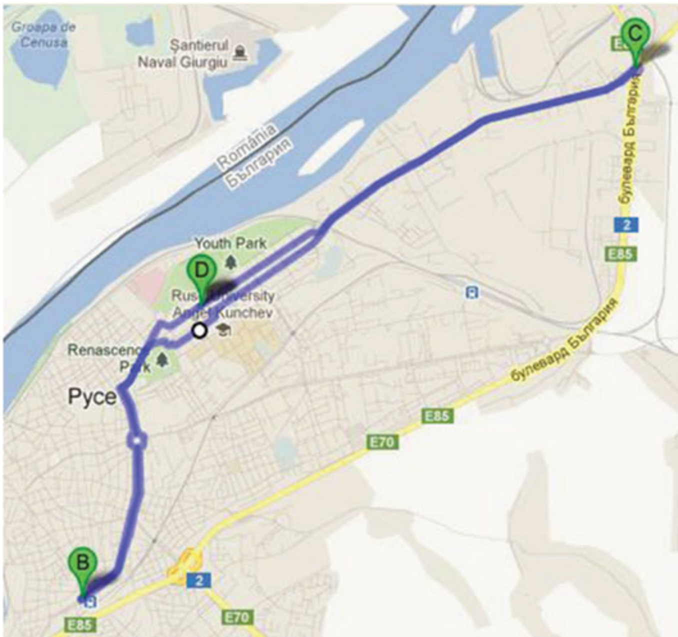


Fig. 7 Route 1 "Rail station—Danube bridge—Rail station"

Fig. 8 Route 2 "Rail station—River station—Rail station"

load of the vehicle was 3 persons (including driver). During the all experiments the AC system was working.

The choice of the routes was realized taking into account the fact that all are with intensive traffic, different traffic regulation and include parts with different inclinations. Before series of road experiments, a verification of the fuel consumption, indicated by the vehicle board computer was done using Flowtronic 205. The difference between board computer and Flowtronic 205 result for the average fuel consumption, passing a distance of 2 km, at different speeds is less than 2%.

Every experiment was repeated 3 times. At the end of the experiments, in the laboratory, the results were proceeded and the graphics were created [23]. All results in urban conditions are summarized in Table 2.

The average fuel consumption of the hybrid vehicle Toyota Yaris is significantly higher from that one indicated from the producer in the technical specification (see Table 2). Possible reason for that difference can be explained with the density of the real traffic in Ruse at peak period and European city cycle. It is obvious that fuel consumption of the HEV on all three routes without "ECO MODE" is higher than that the one with working "ECO MODE". Using "ECO MODE" the vehicle accelerates slowly.

The fuel consumption on the first route without and with working "ECO MODE" is respectively 61.3% and 35.4% higher than indicated in technical specification of

Fig. 9 Route 3 "Rail station—Druzhba 3—Rail station"

the producer. The fuel consumption on the second route without and with working "ECO MODE" is respectively 119.4% and 64.5% higher than indicated in technical specification of the producer. The fuel consumption on the third route without and with working "ECO MODE" is respectively 87.1% and 74.2% higher than indicated in technical specification of the producer.

In urban conditions, the energy saved in the battery and regeneration of the energy during braking are used more active. The less using of the ICE decreases the fuel consumption and energy performance of the hybrid vehicle is similar to that one of the less powerful conventional model Toyota Yaris (P3)—1.0 VVT-i 5 M/T (Table 4).

Study of the fuel consumption of the hybrid vehicle in inter-city conditions
Fuel consumption on three inter-city routs were investigated:

– Route 1 "Ruse—Varna—resort Golden sands—Ruse" (Fig. 10);
– Route 2 "Ruse—Sozopol—Ruse" (Fig. 11);

Table 2 Obtained results for distance S, average speed V_{av}, time t, average fuel consumption Q_{av} and in urban routs, concerning hybrid vehicle and conventional vehicle with similar power

Route	Toyota Yaris (P3) 1.5 HSD Hybrid					Toyota Yaris (P3) 1,0 VVT-i 5 M/T
	Distance S, km	Average speed V_{av}, km/h	Travel time t, min	Q_{av}, l/100 km		Q_r, l/100 km
				Without eco mode	With eco mode	
"Rail station—Danube bridge—Rail station"	15.3	23	30	5.0	4.2	4.9
"Rail station—River station—Rail station"	4.6	21	14	6.8	5.1	6.7
"Rail station—Druzhba 3—Rail station"	6.4	22	12	5.8	5.4	5.8

Fig. 10 Inter-city route 1 "Ruse—Varna—resort Golden sands—Ruse"

Fig. 11 Inter-city route 2 “Ruse—Sozopol—Ruse”

– Route 3 “Ruse—Silistra—Ruse” (Fig. 12).

The choice of the routes was made taking into account combination of the inter-town, high way and urban parts. The combination of the uphill, downhill and horizontal part in the routes is also considered.

Route 1 “Ruse—Varna—resort Golden sands” and return (Fig. 10) includes motion on the first class road Ruse—Shumen, on the high way Shumen—Varna and in urban conditions. Route 2 “Ruse—Sozopol—Ruse” (Fig. 11) has a specific relief (motion uphill, downhill and horizontal parts). The route distance is 300 km. The experiment is done with 2 passengers and working AC system. Route 3 “Ruse—Silistra—Ruse” (Fig. 12) is 116.9 km. The experiment is done with working AC system. The load was 4 passengers in direction Ruse—Silistra and 3 passengers in direction Silistra—Ruse. The route is plane and different number of passengers give the possibility to estimate the influence of the vehicle load on the fuel consumption. During the pass of the routes, the “ECO MODE” was deactivated for all 3 routes. The results for current and average fuel consumption of the hybrid vehicle are presented in Table 3.

Route 1 “Ruse—Varna—resort Golden sands—Ruse”. The obtained results show that average fuel consumption of the whole route is significantly higher than indicated in technical specification of the producer (see Tables 3 and 4). The difference is up to 40–50%. The cause probably is different motion intensity out of the towns and on the high way, in comparison with used European cycle using by the producer to estimate fuel consumption of the hybrid vehicle. Less using the ICE decreases the

Fig. 12 Inter-city route 3 “Ruse—Silistra—Ruse”

Table 3 Obtained results for distance S, average speed V_{av}, time t, average fuel consumption Q_{av} and average route fuel consumption Q_r (two directions) in inter—city routes

Routes	Results				
	S, km	V_{av}, km/h	t, min	Q_{av}, l/100 km	Q_r, l/100 km
Route 1 “Ruse—Varna—resort Golden sands”—with 4 persons	212	77.1	165	5.25	5.18
Route 1 “resort Golden sands—Varna—Ruse”—with 4 persons	212	78.4	163	5.10	
Route 2 “Ruse—Sozopol”—with 2 persons	300	71.8	251	4.5	4.6
Route 2 “Sozopol—Ruse”—with 2 persons	300	70.4	247	4.7	
Route 3 “Ruse—Silistra”—with 4 persons	116.9	62.2	113	5	–
Route 3 “Silistra—Ruse”—with 3 persons	116.9	65	108	4.35	–

Table 4 Fuel consumption Q given by the producer for the hybrid and conventional vehicle with similar power

Conventional models	Q, l/100 km		
	Urban cycle	Inter—city cycle	Combined cycle
Toyota Yaris (P3)—1.5 HSD Hybrid (100 *Hp*)	3.1	3.5	3.5
Toyota Yaris (P3)—1.0 VVT-i 5 M/T (69 *Hp*)	5.7	4.2	4.8

fuel consumption of the hybrid vehicle in urban condition and this way decrease the consumption for whole route. In inter-city conditions, the fuel consumption is similar to this one of the conventional vehicle of the same producer (5.4 l/100 km for combined cycle of motion). In this case, the effect of the hybrid system is minimal.

Route 2 "Ruse—Sozopol—Ruse". Differences of the fuel consumption in separated parts of the route, in two directions are minimal. Exception is this part, which concerns exit and entrance in Ruse because of uphill and downhill motion in different directions of the route. One can see on the figures part with zero consumption. They correspond to passes through small villages, with limited speed less than 50 km/h. During those periods hybrid vehicle was moving on the electric energy only thanks to full charged battery in inter-city conditions. The fuel consumption of the hybrid vehicle on the route is significantly higher than indicated in technical specification of the producer (see Tables 3 and 4).

Route 3 "Ruse—Silistra—Ruse". In inter-city conditions, the fuel consumption is similar to that one of the conventional vehicles of the same producer and the effect of the hybrid system is minimal. Less consumption is registered during the exit of Silistra and during the entrance in Ruse, because of the downhill motion. The difference of 1 person less into return direction causes a less fuel consumption of 0.65 l/100 km.

A complex study of the fuel consumption of a hybrid vehicle Toyota Yaris was done. Original data for motion at different constant speeds were obtained. The economical and energy characteristics of the vehicle was received and analyzed. At low constant speed, the energy consumption is a little higher (Fig. 3), which is a result of low values of the transmission and electric propulsion efficiency. Then the energy consumption slowly goes down. Up to 50 km/h fuel consumption is zero l/100 km, because for the motion, the vehicle use only electric energy (approximately 0.08–0.1 kWh/km) from the battery. At constant speed over 50 km/h, the fuel consumption is practically equal to that one of the conventional variant of the same vehicle. At high-speed conditions, the hybrid vehicle runs using only ICE. It is not appropriate to make comparative analysis of different models hybrid vehicles only on the base of fuel consumption and energy characteristics.

The fuel consumption at urban routes is different for the separated routes (Table 2 and Fig. 7). Probably the differences are generated by the terrain, the traffic and battery recharge. In real urban conditions, at rush hours, the hybrid vehicle has significantly higher consumption than indicated in technical specification of the producer—for studied routes from 61.3 to 119.4%. The usage the "ECO MODE", in urban conditions, reduce the fuel consumption with 7.4–33% for separate routes and average for all routes consists 20%. Improving the fuel consumption is connected with worse dynamic performance.

In the real inter-city conditions, the motion of the hybrid vehicle is essentially realized by the ICE. The investigated vehicle has a 31.4–48% higher fuel consumption than indicated in technical specification of the producer. Usage of the "ECO MODE" in inter-city conditions has no significant effect. The minimal effect (under 4%) is a result of motion in villages with limited speed, basically on the electric energy.

The effect of the hybrid driving system is contradictory. In urban conditions, hybrid system has up to 31.3% less fuel consumption (with "ECO MODE") in comparison with an equivalent conventional model. In Inter-city conditions, the fuel consumption is practically equal to this on of the conventional vehicle Toyota Yaris (P3)—1.0 VVT-i 5 M/T. The effect on the consumption in urban conditions depending on intensity of the motion, road profile, possibility for regeneration, "green wave" etc.

The opinion of the research team is that have to be built-in battery with higher capacity. This action will improve effect of the hybrid system. The existing battery of 0.94 kWh assures a motion of 3 km on horizontal terrain, which is not enough in an urban route of a middle-size East European town.

1.3 Energy Consumption of Electric Bicycle

Moving in urban areas is connected with big intensity, often braking and starting and continuous working of the engines in idle mode. The increased fuel consumption leads to increased level of the air pollutions.

The governments in the different countries apply different measures for stimulation the use of environmentally cleaner vehicles [19, 36–39] and production of electric energy by renewable energy sources [19, 38, 40].

Many European and Asian countries encourage the usage of bicycles and special attention is paid to the bicycle moving infrastructure [38, 39, 41]. One special category of the vehicles is the electric bicycles. They combine some advantages both from the classic bicycle and the electromobile [19] such as less costs for self-movement, typical for the two-wheeled vehicles, possibility for electric operation or help for climbing etc. In the bigger part of the existing ones there is a possibility provided for generating of energy by charging of the battery during braking or descending.

It is well known that the bicycle has a very low energy consumption in comparison of BEV. For the purposes of the research, a team from the Ruse University has worked out an experimental electric bicycle [42] based on a Bulgarian bicycle and electric elements. The general structure of the electric bicycle is shown on Fig. 13.

The electric bicycle is operated by BLDC electric motor 5 with a nominal power of 500 W, built-in the front wheel. It is operated by lithium ion battery 3. The battery

Fig. 13 General view of the electric bicycle: 1—frame; 2—back wheel with a chain mechanism; 3—battery; 4—controller; 5—electric motor; 6—handlebar

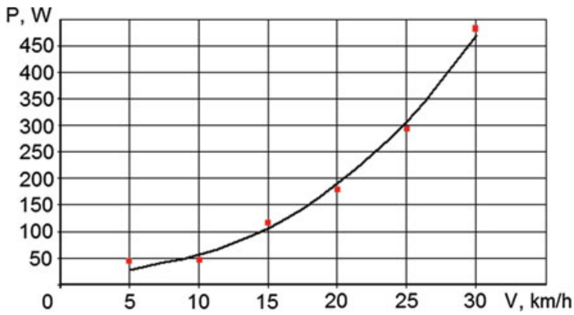


Fig. 14 Dependence of the used motor power P by the speed V

has a working tension of 36 V, capacity 9 Ah and a mass of 3.5 kg. The battery contains 324 Wh electric energy. The total mass of the electric bicycle is 24.4 kg.

The parts for operating and control are assembled on the handlebar. The controller optimizes the working regimes of the electric motor and the regime of regenerative braking. The autopilot provides a constant speed of the electric bicycle thus giving a possibility to free the right hand from the speed regulation lever. The regenerative stopping is operated by a separate button aiming to eliminate the eventual switch on of the mechanical brake system.

The energy consumption of the electric bicycle has been studied during different working regimes. There have been made experiments on a horizontal road in two directions with a five time repeating at constant speeds from 5 to 30 km/h. The total weight of the electric bicycle and the cyclist was 99.4 kg. The power P from the electric motor at different speed V of the electric bicycle is shown at Fig. 14. The

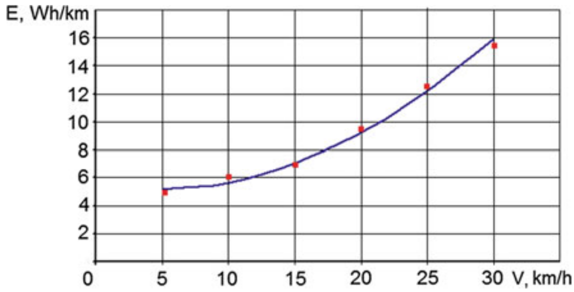


Fig. 15 Dependence of the energy consumption E by the speed V

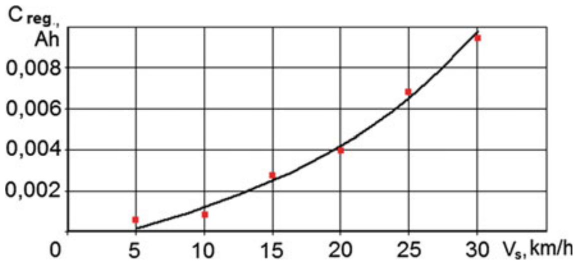


Fig. 16 Dependence of the regenerating capacity in the battery C_{reg} versus initial speed of braking V_s

energy characteristic—energy consumption E per 1 km at different constant speeds V is shown at Fig. 15.

Study on the regenerative braking of the electric bicycle

At serial production the electric bicycles and the sets on the market, the regenerating braking is achieved by the levers for activation the front and the back brake. At the first starting of the lever only the regenerating braking is switched on and after that depending on the power of pressing of the lever is achieved the desired brake delay, accordingly from the two braking systems—the electric and the mechanical.

At present, there are no enough researches for the effectiveness of the regenerative braking of the electric bicycles in urban areas. In [43] it is indicated that depending on the conditions of moving and the slopes of the streets, the regeneration of energy varies from 6 to 14%. The experiments made in city of Ruse during a covered distance of 215 km at some of the routes of the public transport a regeneration of 5.5% is obtained.

The full stop only by electric motor, without using the mechanical brake is impossible. At the beginning there is only regenerating braking and after that it is necessary to switch on some of the braking systems to be achieved a full braking.

There have been made experiments at different initial speed and only regenerative braking has been performed. The results from the studies are presented at Fig. 16. Each full braking or speed reduction through the electric motor increases the run of the electric bicycle and the exploitation time of the mechanical brake system.

It is possible in the infrastructure of the urban area to be realized descending with a speed reduction possibility through the electric motor. With this regard there have

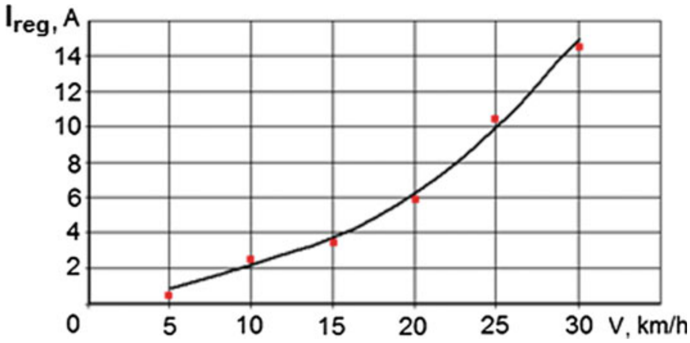


Fig. 17 Dependence of the regenerative current I_{reg} versus speed of the electric bicycle V

been performed experiments of descending at different speed. The results from the experiments are shown at Fig. 17. At the different values of constant speed V is reported the regenerated current I_{reg} which charges the electric battery.

From this characteristics it is seen that upon descending with speed 25 km/h in a regenerating regime for 60 s (the slope is 420 m long) in the battery will be regenerated ~0.17 Ah. At 9 Ah battery capacity, this regenerated capacity is ~2%.

Study the energy consumption for typical routes in the conditions of a medium size town

For the study of the energy efficiency of the electric bicycle there have been chosen three typical routes in the town of Ruse (population ~150,000) with a different profile but with a heavy traffic. They are shown at Figs. 7, 8 and 9. For their visualization a virtual map has been used.

The three routes were passed by two group experiments. Firstly, at the beginning without the help of the cyclist and starting only by using the electric motor for acceleration. Again, the same routes have been passed with the help of the cyclist though the bicycle pedals only at staring until reaching a speed of 5 km/h. All the experiments have been started with fully charged battery. The results are shown at Table 5.

There has been made an experiment also for determination the operating range of the bicycle at a daytime period with a less traffic (Sunday morning). The average results from route 1 showed that with one charge of the battery, the electric bicycle passes a distance of 34.77 km in urban conditions, without using the regenerative braking. The maximum achieved speed was 35.4 km/h and the average speed—23.8 km/h. For the whole pass of the route, the electric bicycle has used 390.49 Wh of energy and average per km—11.2 Wh/km.

From the carried-out research and the analyses of the results, the following conclusions could be made:

Without regeneration of the energy in urban conditions the range of the electric bicycle is about 35 km. Considering the average value of the regenerating energy in a town of Ruse, the run of the electric bicycle could be increased from 5 to 10%.

Table 5 Results from the trials

Parameters	Routes, passed without a help at starting			Routes, passed with a help at starting		
	1	2	3	1	2	3
Passed distance *S*, km	15.03	5.5	4.34	15.77	5.78	4.33
Energy consumption per 1 km passed way, Wh/km	12.8	16.4	18.4	12.5	13.4	13.1
Regenerated energy, %	4.5	5.2	9.5	7.7	10.4	10.7
Maximum speed on the route V_{max}, km/h	36.6	35.8	33.1	35.2	39.8	31.6
Average speed on the route V_{av}, km/h	24.5	22.8	18.4	22.4	21.3	20.6
Time for route passing, min, s	36 min, 46 s	15 min, 5 s	14 min, 5 s	42 min, 10 s	16 min, 16 s	12 min, 36 s

At daytime periods with not so heavy traffic, the run of the electric bicycle could be increased with about 11% due to the smaller number of braking and accelerations.

The studies showed that in a town like Ruse, the use of electric bicycle instead of other vehicles by one person could reduce the air pollutions up to 10 and 15 times compared to the electromobiles and the conventional vehicles.

At speed of 15–25 km/h the used power of the electric motor is from 100 to 300 W and the energy consumption is from 7 to 12 Wh/km which is 6–23 times less than the energy consumption of the electromobiles produced now. There is a bigger effect from the regeneration of energy at the routes including slopes. For example, at the plain route 1 the regeneration is about 5%, but at routes 2 and 3 including slopes the regeneration reaches about 10%.

The level of increasing the effectiveness of the regenerative braking depends on the road infrastructure for moving of bicycles and electric bicycles, and the chosen by the cyclist regimes for speed reduction and braking.

1.4 Energy Consumption of the Auxiliary Systems of Electric Vehicles

An important characteristic of energy performance of the electric vehicle is traveled distance for one charge of battery [16, 18, 44]. Usually, in the technical specification of electric vehicles, the producers give an operational range, which is not precisely detailed concerning the conditions of motion (in city or inter-city traffic, what is the air temperature, what use of the auxiliary systems etc.). For the owners it is very important to know as realistic as possible the remaining travel distance and influence of auxiliary systems on energy consumption and distance [45–48]. That knowledge will ensure a calm and comfortable travel, independent of limited energy autonomy of electric vehicles. The goal of the study is to analyze the influence of different auxiliary systems of electric vehicles on the travel distance at different running conditions and comfort (as temperature in the vehicle, using the lights, audio system etc.).

A significant influence on the energy consumption have auxiliary systems—the second part E_{AS} of relation (1). The approach for their assessment has to be very accurate, especially when the maximal power of those devices is in use, to assure exact determination of travel distance.

The power supply of auxiliary systems is realized by the second (operational) battery at voltage of 12 V. It can be recharged from the traction battery trough DC/DC convertor. The losses during this transformation have to be taken into account by introducing a coefficient marked as η_{DC}. Finally, the specific consumption of the auxiliary systems can be represented as

$$E_{AS} = \frac{1}{\eta_{DC}}(E_{CC} + E_L + E_{WCS} + E_{OS}), \text{kWh/100 km}, \tag{9}$$

where

η_{DC}—is the efficiency coefficient of the convertor between two batteries;
E_{CC}—the specific energy consumption of AC system;
E_L—the specific energy consumption of lights and horn;
E_{WCS}—the specific energy consumption of windows cleaning system;
E_{OS}—the specific energy consumption of other systems as SRS, ABS, TC ESP, electric windows open system etc.

Energy consumption of the separate auxiliary systems

Approximately, the energy consumption of the auxiliary systems presented as % of energy charged in the main (traction) battery is shown in Table 6 [45, 46].

The presented information in Table 6 is more general and does not include all operational conditions of electric vehicles. This is a reason to make a review, concerning influence of different factors on energy consumption of each auxiliary system.

AC system

The normal internal temperature of the air in the compartment have to be 20–23 °C.

Table 6 Energy consumption of some auxiliary systems

Auxiliary systems	Part of traction battery energy, %
AC system – Cooling – Heating	Up to 30% Up to 35%
Power steering	Up to 5%
Braking system	Up to 5%
Other (lights, media, locks etc.)	Up to 5%

To maintain that limits, the energy consumption of AC system depends on temperature difference in and out of the vehicle. Table 7 presents an example concerning needed power of control system at different internal temperatures and high external temperature [45].

The maximal value of the power supply of AC system can achieve 3–5 kW for some vehicle models. As heat device they use electric heater or heat pump.

On Fig. 18 the influence of power consumption of 2 kW (working AC system) on travel distance is illustrated for electric vehicle Tesla Roadster [18].

At speed of 25 km/h, the travel distance per one charge of the battery decreases approximately 2 times when the AC system of 2 kW works. The curves are well represented by the following regression models:

– travel distance without working AC system

$$L = -9 \times 10^{-10} V^6 + 6 \times 10^{-7} V^5 - 0.0002V^4 + 0.0228V^3 - 1.6088V^2 + 50.131V + 116.1, \text{km}. \quad (10)$$

– travel distance with working AC system of 2 kW power

$$L = 4 \times 10^{-6} V^4 + 0.0018V^3 - 0.3157V^2 + 19.881V + 10.837, \text{km}. \quad (11)$$

There are not many researches concerning influence of the external air temperature on the energy consumption. In [49] a Canadian company, on the base of over 7000 travels in the whole North America, have made a generalization of average energy consumption of electric vehicle Nissan Leaf (Fig. 19).

The curve from Fig. 19 is well represented by the regression model

Table 7 Needed power for supply of AC system in function of internal temperature in the passenger compartment

External air temperature, °C	Internal temperature, °C	Needed power, kW
43	21	1.5–2
43	25	1
43	29	0.5

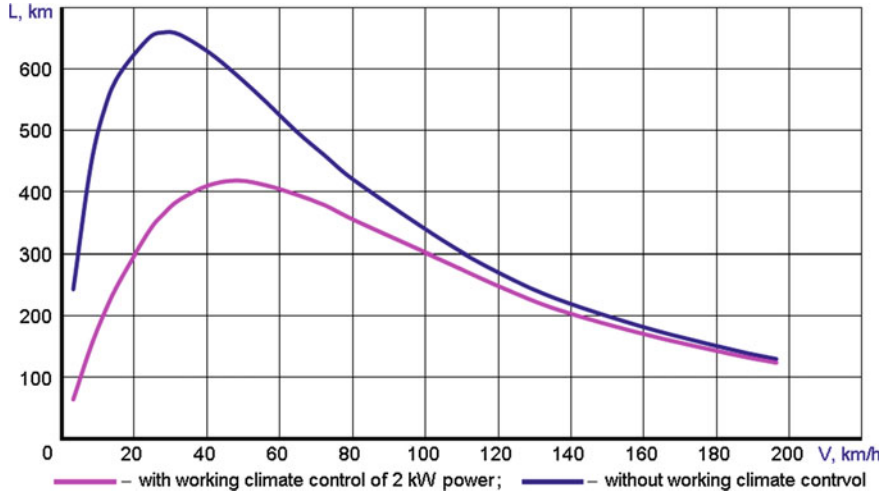


Fig. 18 Influence of AC system power consumption of 2 kW on the traveled distance per one charge of battery for electric vehicle Tesla Roadster [140]

$$E = 8 \times 10^{-9}t^6 - 3 \times 10^{-6}t^5 + 0.0001t^4 + 0.0028t^3 - 0.0546t^2 - 2.797t + 206.22,\ \text{Wh/km}. \quad (12)$$

The same data is shown on Fig. 20 as influence on the travel distance L [50]. The respective regression model is

$$L = 6 \times 10^{-8}t^6 - 4 \times 10^{-7}t^5 - 0.0001t^4 - 0.0004t^3 + 0.0544t^2 + 1.3326t + 99.995,\ \text{km}. \quad (13)$$

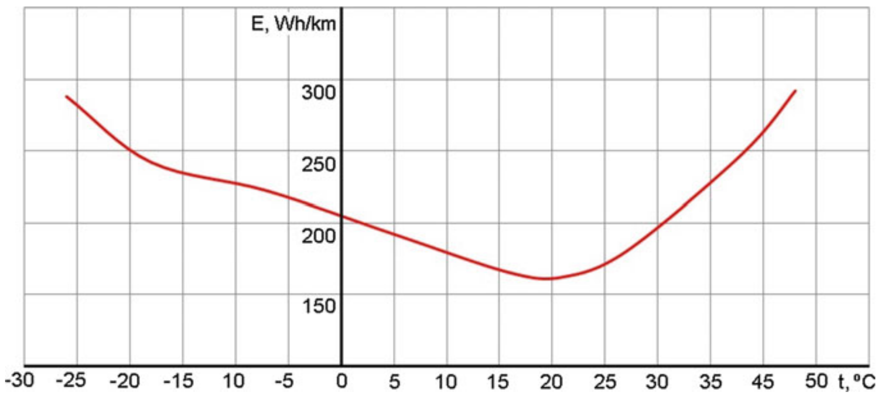


Fig. 19 Influence of the external air temperature on the specific energy consumption of electric vehicle Nissan Leaf [140]

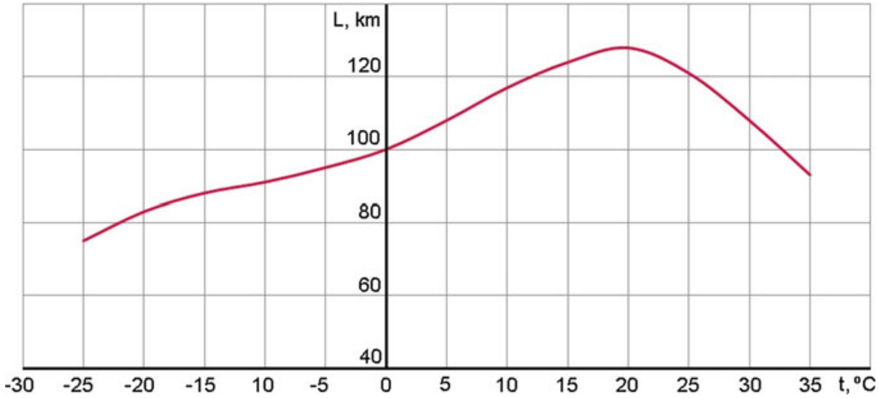


Fig. 20 Influence of the external air temperature on the range of electric vehicle Nissan Leaf [140]

It is obvious that external air temperature has a significant influence on the energy consumption of electric vehicle. The explanation is connected with energy for heating or cooling but also with efficiency of battery at different temperatures. Taking into account these two factors, one can see an optimal external air temperature at which the energy consumption is minimal and travel distance is maximal (Figs. 19 and 20). This optimal value is approximately 20 °C.

Light system, light signalization and horn

The energy consumption of the light system and signalization depend on twenty-four-hour period—if the travel is realized in the day or in the night. That is especially important for long and short front lights. Usage of elements of light system and signalization, during 100 km travel, are presented in Table 8. The data from different sources [47, 48] was proceeded and a generalization was done.

The calculations show that maximal energy consumption of light system using conventional lamps at night travel is about 150 Wh/100 km. Usage of the LED-lamps decrease the consumption 2.2–3.8 times [44, 47, 48, 51, 52].

In specialized literature there is no information concerning time for use and energy consumption of the horn. Probably, because the value of used energy is insignificant.

Audio system

Energy consumption depends on the power characteristic and time for use of the system. Usually built in systems have a power supply of about 200 W. The time for use of the audio system vary in wide limits and correspond to driver and passenger's needs.

Actual energy consumption also depends on sound level. Some authors [17], in simulation models, give an average power supply of 20 W for audio system and use ratio approximately 75% of travel time.

Table 8 The statistical data for usage of the elements of light system and signalization

Elements	Working time, min/100 km	Power consumption for vehicle with conventional lamps, W	Power consumption for electric vehicle with LED-lamps, W
Daily lights	116.5	40	8
Long lights	9.8[a]	60	34.4
Short lights	97.6[a]	55	54
Left blinker	5.8	21	6.9
Right blinker	4.6	21	6.9
Stop-lights	18.9	21	5.6
Stop-lights (central position)	18.9	21	3
Rear-lights	107.4	5	1.7
Registration table lights	107.4	5	0.5
Reverse motion light	0.9	21	5.2

[a]Night time driving only

Windows cleaning system and seat heating

This system uses electric motors with maximal power of 30–50 W. Time of use strongly depends on the weather (if there is the rain or snow).

The average consumption of the seat heating system is 30 W and mean use ratio—5% of time [17].

Other systems

The main included in this group are: system of passive safety—SRS; Anti-lock Braking System—ABS; Traction Control System—TC; Dynamic Stability System—ESP; systems for opening and closing of door windows and roof. The biggest consummators form this group are the systems for active safety, but value of energy depends on driving style.

Internal losses in traction battery

Depending on the battery type, during idle time (no traction) the additional losses can present for maintenance of the working temperature. For example, some metal-hydride batteries work at a temperature of approximately 300 °C and permanent consummation power of 60–80 W for temperature maintenance. If the capacity of the battery is 18 kWh after 10 days idle time it will be fully discharged.

Internal losses of the Lithium-ion batteries depend on the number of the connected cells and Battery Management System—BMS.

Every battery has a limited period of exploitation. To extend that period the power electronics controls charge/discharge process. This means that only a part of the battery capacity can be used—full charge and discharge are unavailable. This is made to provide the possibility for accumulation of the regenerative braking energy.

Influence of the regeneration on the travel distance

Regeneration of electric energy is possible during braking process. Depending on running conditions and route characteristic, the maximal value of regenerative energy vary from 10 to 25% in city conditions [53, 54]. The experimental results [53, 54] show that braking deceleration in limits 2–3 m/s^2 can assure efficiency of regenerative braking up to 90% and minimal transformation of kinetic energy to heat and friction in mechanical braking system (Fig. 21).

At bigger decelerations, the battery cannot receive regenerative energy, the mechanical braking system is switched on and all two system work together to provide required deceleration (Fig. 22).

To improve usage of regenerative energy they often build in traction system supercapacitors (especially in buses).

On the basis of investigation and analysis of influence of the running conditions and auxiliary systems on the energy consumption of an electric vehicle, the following conclusions can be formulated. The minimal energy consumption of electric vehicles is realized at lower speed—up to 40 km/h. These values are significantly lower than respective for conventional vehicles—approximately 65 km/h.

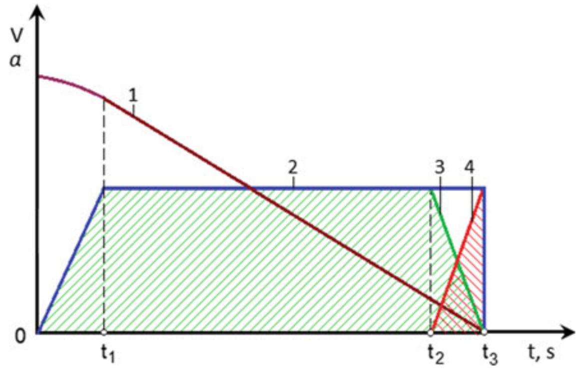


Fig. 21 Example of realizing of regenerative braking [19]: 1—vehicle speed; 2, 3—deceleration, realized only by regenerative braking; 4—deceleration, realized only by mechanical braking system [19, 140]

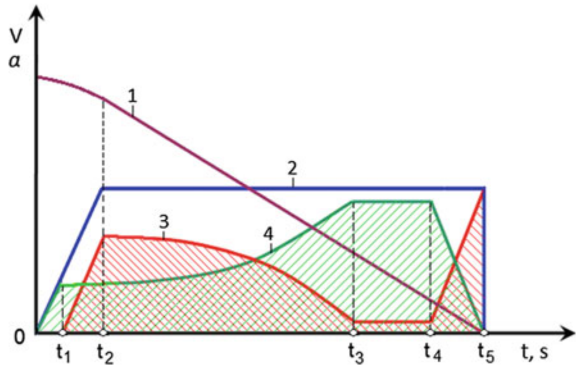


Fig. 22 Interaction of the two braking systems during formation of constant deceleration [19]: 1—vehicle speed; 2—total deceleration; 3—deceleration, realized by mechanical braking system; 4—deceleration, realized by regenerative braking [19, 140]

At low speed, for example 5 km/h (hard traffic and jams), the energy consumption can be equal to that one at 100 km/h. The cause for this is low efficiency of the drive train and big part of energy consumption for supply of the auxiliary systems at low speed motion. At high speed—over 50 km/h, the influence of the part of auxiliary systems in total energy consumption decrease and the energy consumption spend for air resistance becomes dominant.

At some values of speed and weather conditions, the energy consumption for the supply of auxiliary systems can decrease twice travel distance of the vehicle.

The minimal energy consumption of auxiliary systems is realized at external air temperature of 20 °C, at which the biggest travel distance is achieved.

The light system and signalization consume about 1% of total energy consumption of electric vehicle.

It is very important to indicate that all above regarded characteristics do not present exactly total spent energy and generated emissions during whole "LIFE" of the vehicle. It is obviously that one other assessment has to be applied.

2 Life Cycle Assessment of Vehicles, Using Different Types of Fuels or Electricity. Energy Consumption and CO_2 Emissions

During the last decade, the Life cycle assessment (LCA) became a dominant methodology into researches concerning sustainable development of a product [55]. LCA is applicable also for study influence of a production process on the environment. Existing researches [56–61] about the effectiveness of fuel production and use in vehicles stimulate environment protection and support development in this area.

Building of a sustainable transport system is connected with modernization of existing vehicle park using ecological vehicles. The alternative vehicles can be classified as:

– Gasoline fuel vehicles (GV);
– Flexible fuel vehicles (FFV);
– Dedicated vehicles (DV);
– Bi-fuel vehicles (BFV);
– Dual fuel vehicles (DFV);
– Battery electric vehicles (BEV);
– Hybrid electric vehicles (HEV);
– Hydrogen fuel-cell vehicles (FCV);
– Compressed-air vehicles (CAV).

In this study, the following values of the quantities and assumptions are used:

– equal mass of the all types of vehicles;
– energy consumption of the BEV—0.210 kWh/km;
– fuel consumption of the GV—7.6 l/100 km of gasoline;

- capacity of the battery of BEV—40 kWh;
- equal range of the life cycle all types of vehicles—290,000 km;
- energy for vehicle production—11,900 kWh [59];
- efficiency of NPS—29.5% [62];
- efficiency of TPS using coal—26% [63];
- efficiency of TPS using natural gas—40% [64];
- efficiency of water power station (WPS)—60% [65];
- efficiency of wind power station (WiPS)—40%;
- average efficiency of power stations using renewable energy sources—50%;
- losses for transport and distribution of the electricity—5% [66];
- efficiency of gasoline fuel production—89.1% [67];
- efficiency of liquid petroleum gas (LPG) fuel production—94% [67];
- efficiency of natural gas (NG) fuel production—91% [67];
- losses due to leakage of NG—1.5% [68];
- losses due to transformation of NG in liquid phase—8% [69];
- generated CO_2 emissions during burning process of: gasoline—240.82 g/kWh; NG—183.96 g/kWh; LPG—214.48 g/kWh [60];
- global warming potential (GWP) of NG—25 [66];
- emission factors of electricity production for Bulgaria, Poland, Norway and average for EU-28 are respectively—669,980, 17 и 447 g/kWh [59, 70];
- in LSA of different types of vehicles, used primary energy and generated emissions due to fuel transportation are not included. Their values can be different for each country. This way a more precise analysis of advantages and disadvantages of separate type of vehicles can be done.

2.1 Life Cycle Assessment of Electric and Conventional Vehicles

In view of decreasing the impact of vehicles on global warming in recent years, more and more electric vehicles replace the conventional ones. Following this trend, a lot of companies direct their efforts at producing vehicles with electric propulsion using Li-ion battery. An electric vehicle at appropriate running conditions can be more effective than the conventional one in terms of environment safety. The general structure of an electric vehicle is presented on Fig. 23. This kind of vehicles use the electric energy accumulated in the traction battery, which supplies the electric motor. Different kinds of batteries (Li-ion, $LiFePO_4$ etc.) and electric motors (PMDC, BLDC, AC etc.) exist.

There are studies [68, 71–74] of the effectiveness of electric vehicle versus conventional ones in terms of emissions of greenhouse gases adjusted to carbon dioxide equivalent (CO_2). Usually, this type of studies is done using the Life Cycle Assessment (LCA) method [55] and the comparison is made for the energy consumption and/or CO_2 emissions. LCA is used to assess the environmental impact during all

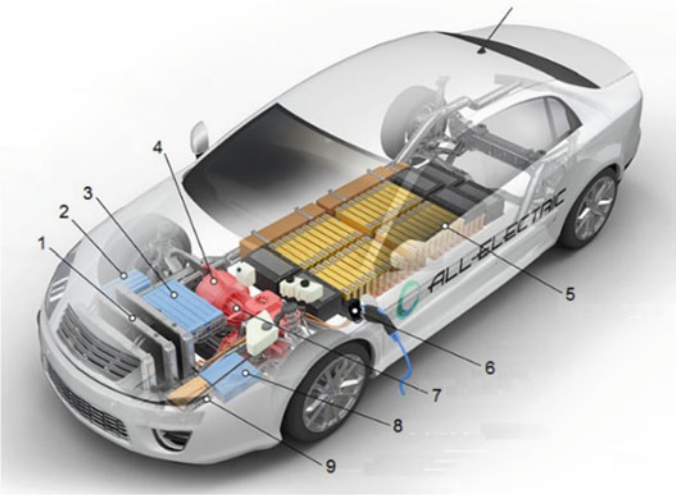


Fig. 23 Structure of an electric vehicle: 1—cooling system; 2—DC/DC convertor; 3—power electronics; 4—electric motor; 5—traction battery; 6—charging contact; 7—transmission; 8—charging device; 9—operational battery [74]

stages of vehicle life including extraction of raw materials and energy source, materials processing, vehicle manufacture, distribution (transport), use (motion) including maintenance and repair, and finally recycling or disposal [55]. The interest of researchers [66, 68, 71–73, 75–79], and our interest is focused mainly on the results for energy consumption and CO_2 emissions, obtained through LCA.

In [71] different models of vehicles are studied. The main conclusion is that all the BEVs researched have lower CO_2 emissions than ICE vehicles when the electricity comes from the European mix. The well-to-wheel CO_2 emissions are reduced by approximately 50% as compared to a similar internal combustion engine vehicle. It is not clear what is the energy spent for battery production.

Study [68] calculates the energy inputs and CO_2 equivalent emissions of a conventional gasoline vehicle, a hybrid vehicle, and a battery electric vehicle. The aim is to determine the lifecycle environmental costs of each vehicle type in conditions of California. The main purpose of the study is to examine the environmental impact of each vehicle type, taking into account lifecycle energy usage and both CO_2 equivalents and air pollution emitted. The models are developed and the impact of a variety of factors, including carbon intensity of gasoline and electricity, varied electricity mixes, battery lifetime, and fuel economy is studied. The cost effectiveness for each vehicle type was also calculated.

Study [72] models the relative impact of new BEVs and ICEVs in the US for the year 2015, and it projects the economic and environmental impact of BEVs and ICEVs over the entire assumed twenty-year lifetime of a US passenger vehicle.

A lot of sources [18, 75, 77, 78, 80–84] contain particular data about the elements and processes included in LCA of vehicles, but some of them are fragmentary and contradictory, which does not permit appropriate use for comparative analysis. The results from the above-mentioned studies show that the average electric energy mix of the respective country has the main impact on CO_2 emissions. A full comparative analysis, based on the LCA method and concerning used energy and generated CO_2 emissions of electric and conventional vehicles in Bulgaria does not exist. The present study is concerned with that problem. LCA of electric and conventional vehicles, based on data about the electric energy mix in some specific EU countries (like Norway, Poland and Bulgaria) and in EU-28, is made.

The generated emissions in CO_2 equivalent for production of 1 kWh electric energy depend on the electric energy mix for the respective country. In Europe, the larger part of electricity is produced by thermal power stations using coal (TPS), nuclear power stations (NPS) and stations using renewable energy sources (RES). In some countries like Holland, the main part of the electricity is produced using natural gas (NG).

In Table 9 the electric energy mix for European counties (EU-28) is presented [65, 80, 83]. In the last row, similar information about Norway is given [80, 83]. In some of the countries, the total percentage is not a full 100% because of using small local electric generators, which is not significant for the statistics.

During the production process, power stations' direct and indirect emissions are generated. The volume of that emission depends on the life cycle of the power station. For example, production of electricity from NPS and from RES has no direct emissions and this is the reason to use electricity produced in such stations for charging electric vehicles.

The summarized information for the countries of EU-28 concerning the emissions of CO_2 generated for the production of 1 kWh electric energy is given in Table 10 [66, 83, 85]. The whole life cycle of the used primary energy source is taken into account. In different countries, even with the same type of primary energy source, the volume of emissions may not be equal. Many factors influence these emissions (like needed energy for production and transport of the fuel, using the innovative technologies in production process etc.), but they will not be analyzed in this study. For a correct LCE of the electric and conventional vehicles all spent energy, including energy for production the primary energy source, for vehicle and battery production, for using the vehicle and finally for utilizing the old components, have to be considered.

The fuel consumption of the GV is determined based on the specific energy and efficiency of its internal combustion engine, and with the assumption to have the same volume of energy as that one used for motion of the BEV [68]. In the values of efficiency of different power stations, the losses for extraction of the primary energy sources (coal, natural gas etc.) are taken into account.

The performance of the BEV basically depends on the type of traction battery. The production technology of Lithium-ion battery for electric vehicles is not so cheap in comparison with traditional lead-acid battery.

The energy spent for the production, transport, recycling etc. of the most popular types of battery was calculated on the basis of data from [75] and is shown in Fig. 24. Our study about battery recycling confirms the popular opinion that this process is not economically effective because of high energy consumption and waste

Table 9 Electric energy production (mix) of the EU-28 countries and Norway [65, 80, 83]

Country	Share of total production, %				
	Nuclear energy	Thermal power-plant			Renewable energy
		Solid fuels	Natural gas	Crude oil	
Austria	0.0	0.0	8.7	7.3	78.0
Belgium	65.0	0.0	0.0	0.0	28.5
Bulgaria	33.2	48.7	0.7	0.2	17.0
Croatia	0.0	0.0	33.5	15.6	50.7
Cyprus	0.0	0.0	0.0	0.0	97.4
Czech Republic	24.2	58.6	0.7	0.7	14.9
Denmark	0.0	0.0	26.4	48.7	22.5
Estonia	0.0	75.6	0.0	0.0	23.2
Finland	34.2	4.8	0.0	0.4	59.3
France	82.5	0.0	0.0	0.8	15.7
Germany	19.8	35.9	5.3	3.0	32.5
Greece	0.0	67.0	0.1	0.7	31.2
Hungary	36.7	13.6	12.2	7.6	29.0
Ireland	0.0	39.8	5.6	0.0	51.3
Italy	0.0	0.1	15.3	16.1	65.2
Latvia	0.0	0.0	0.0	0.0	99.6
Lithuania	0.0	1.3	0.0	4.8	92.5
Luxembourg	0.0	0.0	0.0	0.0	76.9
Malta	0.0	0.0	0.0	0.0	100.0
Netherlands	2.2	0.0	82.0	4.3	10.1
Poland	0.0	79.6	5.5	1.4	12.8
Portugal	0.0	0.0	0.0	0.0	97.7
Romania	11.3	17.7	33.0	15.6	22.3
Slovakia	62.6	7.8	1.2	0.2	25.2
Slovenia	43.0	25.4	0.1	0.0	30.2
Spain	44.2	3.7	0.2	0.7	50.5
Sweden	43.2	0.3	0.0	0.0	54.6
United Kingdom	15.3	4.3	30.1	39.3	10.0
EU-28	**28.9**	**18.9**	**14.0**	**9.8**	**26.7**
Norway	0.0	1.4	0.0	0.0	98.6

Table 10 Emissions of CO_2 in the production of electricity for EU-28 Member States [66] and Norway [83], g/kWh

Country	Gross electricity production (combustion only)	Gross electricity production (with upstream)	Net electricity production (with upstream)	Electricity consumed at HV (with upstream)	Electricity consumed at LV (with upstream)
Austria	133	151	156	322	334
Belgium	188	224	233	261	267
Bulgaria	507	532	585	618	669
Croatia	231	273	282	487	524
Cyprus	646	737	773	787	810
Czech Republic	518	545	587	657	685
Denmark	316	368	386	364	377
Estonia	1020	1022	1152	878	944
Finland	171	200	209	207	211
France	66	88	92	100	105
Germany	485	534	567	599	615
Greece	655	695	755	732	767
Hungary	310	340	368	383	407
Ireland	459	533	555	588	617
Italy	358	427	444	413	431
Latvia	134	173	185	1110	1168
Lithuania	204	246	262	370	390
Luxembourg	236	288	283	508	513
Malta	731	831	868	954	1032
Netherlands	479	559	582	555	569
Poland	770	847	929	937	980
Portugal	295	346	355	372	400
Romania	356	379	413	449	492
Slovakia	173	199	211	412	420
Slovenia	315	329	351	309	321
Spain	248	295	305	321	341
Sweden	16	24	25	45	47
United Kingdom	469	555	584	593	623
EU-28	**340**	**387**	**407**	**428**	**447**
Norway	–	–	–	–	17

products presence. Probably in the future battery recycling will be oriented basically for ecological effect and observance of ecological law.

The results show that the life cycle of Li-ion battery needs about 420 kWh per each kWh of battery capacity. For a middle size battery of 40 kWh capacity, approximately 16,800 kWh energy will be used during the life cycle of the BEV, if only one battery is used during the life cycle of BEV (range of 290,000 km). The battery construction permits repair and change of elements. According to some authors [68] it is reasonable to make calculation for 1.5 batteries. In this case, the energy for the life cycle of battery will be one and half times more.

Taking into account the values of the energy spent for vehicle production, battery life cycle and energy or fuel for passing a distance of 290,000 km, the needed energy for the life cycle of BEV or GV can be calculated.

The obtained results for primary energy used in the life cycle of BEV, produced and driven in 4 countries, are presented in Fig. 25a. The energy mix and efficiency of the power station for different countries are used in the calculations.

Generally, the life cycle of the gasoline GV, produced and driven in Bulgaria, needs approximately 309,750 kWh of primary energy. About 86.5% of the life cycle energy is spent on motion. This percentage depends on the energy for vehicle production in the respective country and the last one depends on the energy mix. The energy for motion/ driving changes insignificantly in different countries and basically depends on the losses in the fuel production process. Other stages of the life cycle of GV like production of vehicle and parts, their transportation etc. consume less energy—13.5% of life cycle energy or approximately 42,000 kWh.

The fuel consumption of the vehicle is determined on the basis of fuel calorific value and efficiency of the gasoline engine so that a match with energy used by the electric vehicle presents [68]. Accepted values of power plants efficiency take into account also the losses in the production of respective fuels.

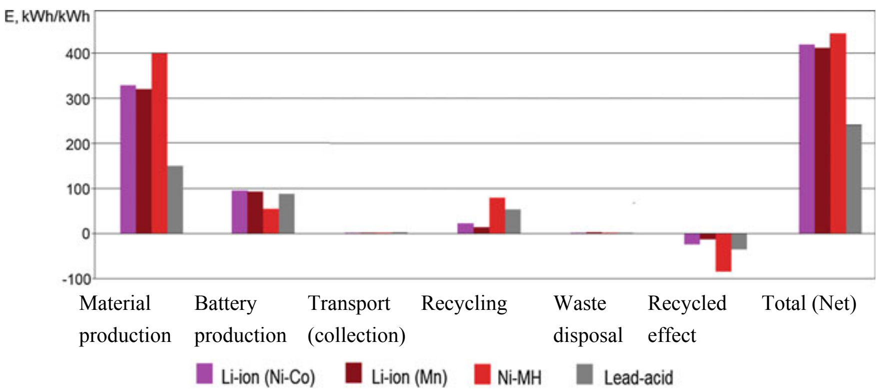


Fig. 24 Energy spent for production and recycling per 1 kWh of capacity of the different battery types [74]

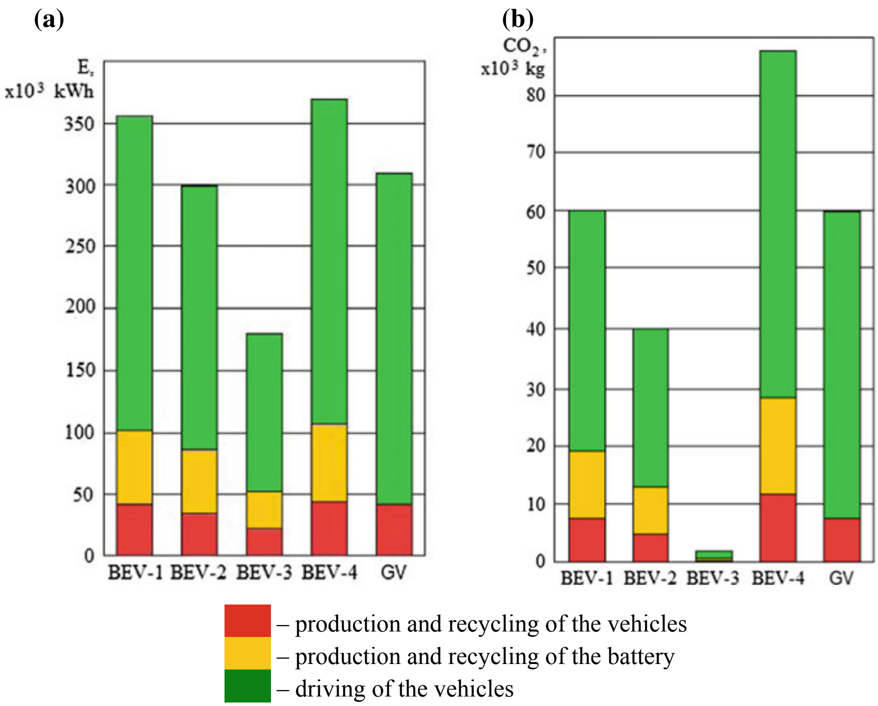


Fig. 25 Life cycle of primary energy (**a**) and CO_2 emission (**b**). BEV-1—production and driving in Bulgaria; BEV-2—production and driving with data for EU-28; BEV-3—production and driving in Norway; BEV-4—production and driving in Poland

The results obtained for the primary energy consumed for the life cycle of the BEV and the GV are shown in Fig. 25a [74]. The results represent 4 typical examples—3 countries and EU, which have very different energy mixes.

Overall, the GV for life cycle (production, transport, exploitation, recycling and disposal of waste), needs approximately 309,750 kWh of primary energy, while the BEV-1, including the traction battery needs 355,210 kWh. Obviously, the life cycle of BEV-1 requires approximately 15% more primary energy than GV produced and operated in Bulgaria (Fig. 25).

For the GV vehicle, approximately 86.5% of the life cycle energy is spent during exploitation. This percentage for the different countries will depend mainly on the energy spent for manufacturing the vehicle, which depends on the country's energy mix. The energy needed to operate the vehicle for the different countries changes insignificantly and will depend mainly on the losses in fuel production. Other life cycle stages, such as vehicle production and spare parts, waste transportation and disposal, require much less energy—13.5% of the total life cycle energy or approximately 42,000 kWh.

In the case of an electric vehicle, the most energy is used for charging the battery—71.5% of the total life cycle energy. Battery production also has a significant impact—16.7% of total energy for the life cycle or 59,290 kWh. The energy at the stages of production of electric vehicle and spare parts, transportation and disposal of waste is approximately 11.8% of the total energy or 42,000 kWh (as much as the GV vehicle).

For the BEV-2 produced and operated with the EU-28 average mix (Table 10), the primary life cycle energy requirement is approximately 16% lower than the BEV-1.

The most energy efficient is the BEV-3—produced and operated in Norway. Primary energy is approximately twice less (49%) than BEV-1. In this case, the BEV-3 will save more than 42% of the primary energy compared to the GV produced in Bulgaria, and 38% lower than GV produced in Norway.

The most inefficient in terms of primary energy consumption is the BEV-4 produced and operated in Poland—about 51% more energy than that the BEV-3.

The generated CO_2 emissions for the life cycle of above-mentioned vehicles are shown in Fig. 25b. The BEV-1 has 59,940 kg of CO_2 emissions. It is almost as good as the petrol vehicle GV—59,750 kg. However, the advantage has to be given to an electric vehicle, because it doesn't generate harmful emissions where operates—the emissions are emitted where the electricity is produced.

The electric vehicle BEV-2 has lower emissions (40,050 kg) compared to BEV-1 by 31%. The minimal value of the CO_2 emissions has life cycle of the BEV-3—1530 kg, or 39 times less than BEV-1 (as much as GV), 26 times less than BEV-2 and nearly 59 times less than BEV-4. Compared to a GV produced in the same country, CO_2 emissions of BEV-3 are approximately 34 times less (due to lower emissions at the vehicle production stage).

BEV-4 has the highest level of energy consumption and generated emissions. It is produced and driven in Poland, where 78.6% of the electricity is from thermal power stations using coal. The most effective one is BEV-3 produced and driven in Norway, where the part of renewable energy is 98.6%. The analysis of these results shows the most effective way to increase the effectiveness and to reduce the emissions of BEV—change the energy mix of the country by using more nuclear power stations and renewable energy sources. The process will also cause change of the emissions for the life cycle of BEV. This effect is illustrated in Fig. 26 for energy mix and CO_2 emissions in Bulgaria—0.669 kg/kWh (see Table 10).

For example, if the level of emissions decreases to 0.4 kg/kWh, for the life cycle of BEV 24,126 kg of CO_2 can be saved. On the contrary, if the energy mix is changed and the part of TPS using coal increases, as a result at emission level 0.9 kg/kWh, the generated emissions for the life cycle of the BEV will exceed the respective ones for the GV by about 20,717 kg.

The relation is well approximated with the following linear equation

$$CO_2 = -89{,}686\,c + 60{,}000, \text{kg}, \tag{14}$$

where c is level of the generated CO_2 emissions, kg/kWh.

On the basis of statistical data for the energy mix and generated CO_2 emissions for different EU countries an LCE concerning the energy consumption and CO_2

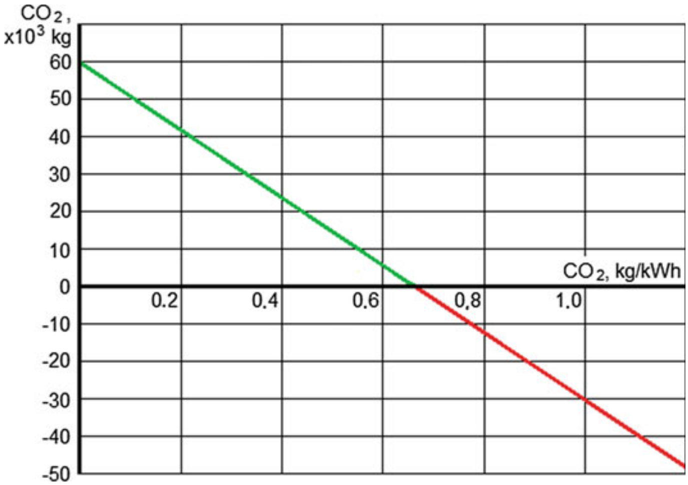


Fig. 26 Determination of possible CO_2 savings for the life cycle of the electric vehicle depending on the emission factor [74]

emissions of BEV and GV was done. The variants in the different countries were described. At conditions in Bulgaria (energy mix for year 2015 and level of emissions for the electricity production of 669 kg/kWh), the BEV-1 and the GV have practically equal emissions for their life cycle. The priority must be given to BEV-1 because the emissions related to the electric vehicle are generated where electricity is produced—not in big towns.

Use of RES for electricity production can reduce CO_2 emissions for the life cycle of BEV by up to 40 times in comparison to GV. A good example in this direction is Norway where 98.6% of energy is produced from RES, the life cycle energy of BEV is 40% less than the average one for EU-28 countries. The emissions are 26 times less than the average one for EU-28 countries. A negative example can be the life cycle of BEV in Poland. As a large part of electricity is produced in coal TPS the primary energy and level of the emissions are very high.

The LCE and the analysis of the results shows that the most effective way to increase the effectiveness and to reduce the emissions of BEV is changing the energy mix of the country by using more nuclear power stations and renewable energy sources.

The production technology of LI-ion battery is continuously developed, but it is still an obstacle for replacing conventional vehicles with battery electric vehicles. Battery recycling now is not an effective process and in the future ecological problems are possible.

2.2 Impact of Renewable Energy on the Environmental Efficiency of Electric Vehicles

The exploitation of battery electric vehicles (BEV) is related to the use of electrical energy to charge their batteries. This energy is produced in different types of power plants that determine the energy mix of a country. As an alternative to reducing dependence on fossil fuels, the impact of vehicles on the emission of air pollution and their impact on global warming, it is the replacement of the vehicle fleet with electric vehicles. A large number of studies [66, 71, 73, 86–89], regarding electric vehicle ecologically efficiency compared to a conventional vehicle (GV), concerning carbon dioxide emissions, have been published. It is Impossible to analyze all these studies in a single work.

For example, in [71] the study focuses on the efficiency of primary energy use for life cycle and CO_2 emissions associated with the operation of electric vehicles in the Netherlands.

In [68] the impact on the environment of each type of vehicle in the state of California is analyzed, taking into account the life cycle energy consumption and CO_2 emissions in the air. With respect to the environmental impact, BEV is determined to have the least overall impact, followed by the hybrid, and finally the GV. In [72] an economic analysis of the cost and environmental impact of electric vehicles with lithium-ion batteries compared to GV with internal combustion engines (ICE) is made. This study developed models for relative impact of the new BEV and GV in the US on the environment for 2015.

It is common in all publications that the main problems faced by BEV are related to the manufacture of batteries and the construction of the appropriate infrastructure for their charging and servicing. It confirms the main influence on their efficiency of the energy mix in the production of electricity.

To what extent the electric vehicle is more effective compared to a conventional vehicle during its entire life cycle, in terms of energy consumption and emissions, it is not clearly determined. The researchers are incomplete and in a number of cases, contradictory.

The present article regards the contribution of renewable energy to increasing the efficiency of electric vehicles in terms of energy used and CO_2 emissions during their entire life cycle for EU-28 countries.

Electricity produced from different energy sources has an impact on the environmental performance of electric vehicles. Table 11 summarizes the results of several studies of conventional technologies and generated CO_2 emissions in the production of 1 kWh of electricity from fossil fuels, nuclear energy, wind energy, solar energy from photovoltaics, hydropower and biomass [86–89].

The emission variation interval depends on the technologies used, carbon content and fuel quality, climatic conditions, etc., taking into account the emissions throughout the life cycle of the power plants—construction, operation and recycling. For this reason, in the production of electricity, emitted CO_2 emissions can be classified to

Table 11 Summary of life cycle GHG emissions for selected power plants, CO_2eq, g/kWh

Technology	Direct emissions	General emissions	Mean
Lignite	800–1700	1100–1700	1100
Coal	800–1000	950–1250	1000
Oil	700–800	500–1200	800
Natural gas	360–575	440–780	580
Nuclear	0.74–1.30	2.8–24	10
Solar PV	–	43–73	58
Wind	–	8–30	17
Hydro	–	1–34	8
Biomass	–	35–99	70

direct—during power plant operation and total emissions—over the whole life cycle of power plants and fuels used.

In Table 10 the energy mix of the member states of the EU-28 and Norway is given [83]. For the different countries, the share of generated electricity from the main types of power plants such as thermal power plants using coal, nuclear, and renewable energy (RES) is different. Therefore, as an assessment of the impact of the country's energy mix on CO_2 emissions in the production of 1 kWh of electricity (Table 10), the so-called "*emission factor*" is used [66]. For electric vehicles consuming electricity for charging the battery, the emission factor data from the last column is used.

Norwegian energy mix is as follows: 1.4%—TPP with solid fuels, 2.7%—WPP and 95.9%—HPP and ocean power [80]. In Norway, CO_2 emissions of 17 g/kWh are generated [83].

If the data from Tables 9 and 10 is analyzed, it can be established that a significant influence on the emission factor has produced energy from NPP and RES. The share of electricity from RES in the final electricity consumption for the E-28 countries in 2017 is shown in Fig. 27 [90].

For the means of transport, the share of energy from renewable energy sources in relation to total energy is of ecological importance. This share for the EU-28 countries, for 2017 is shown in Fig. 28 [91].

The CO_2 emissions emitted in the production and recycling of the electric vehicle, excluding the battery, can be described with the following relation

$$CO_2 = c\,E_{PE}\frac{1}{L},\ \text{g/km}, \tag{15}$$

where

c—is the emission factor in the production of electricity, g/kWh;
E_{PE}—the energy required to produce the electric vehicle, kWh;
L—life cycle range of the vehicle, km.

Using renewable energy can significantly reduce CO_2 emissions from vehicle production and recycling. For example, in Norway with an emission factor of 17 g/kWh,

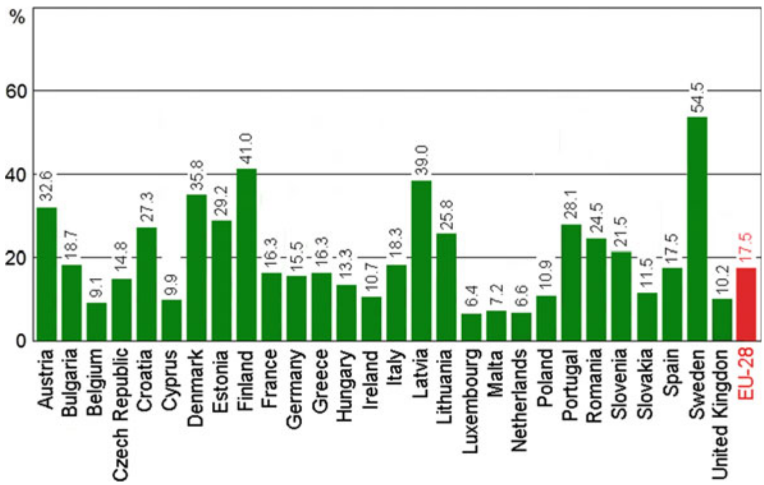


Fig. 27 Percentage share of electricity from RES in final electricity consumption for the E-28 countries in 2017 [75]

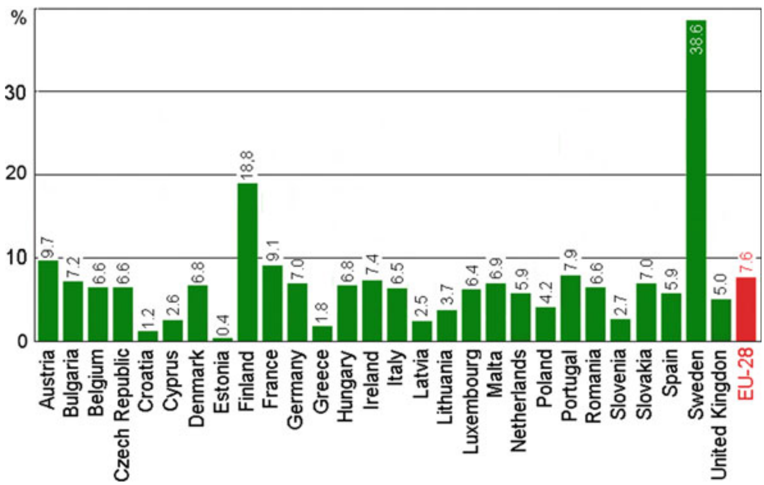


Fig. 28 Percentage of the used electricity from RES in transport for the E-28 countries in 2017 [75]

CO_2 emissions during the production and recycling of electric vehicles would be reduced by approximately 26 times the EU-28 average emission factor.

The performance of electric vehicles depends mainly on the type of traction battery. Lithium-ion batteries, specially designed for electric vehicles, are still produced using new, nontraditional technologies. In the contrary, manufacturing of the lead acid batteries uses well-known and cheaper technologies. Energy costs for production, transportation, recycling, etc. for different types of traction battery are shown schematically in Fig. 24 [75].

The air pollution, as equivalent of CO_2 emissions, due to the production, transportation, recycling of battery etc., can be represented by the following mathematical model

$$CO_2 = c\, E_{PB}\, C_B \frac{1}{L}, \text{ g/km}, \tag{16}$$

where

E_{PB}—is the specific energy kWh for the production of a battery with 1 kWh capacity;
C_B—battery capacity, kWh.

Based on Fig. 24, the following average values of energy costs for life cycle of the batteries can be adopted: for Li-ion (Ni-Co) battery—420 kWh/kWh; for Li-ion (Mn)—410 kWh/kWh; for Ni-MH—450 kWh/kWh and Lead-acid—240 kWh/kWh.

The apparent effect of the electricity source on CO_2 air pollution in the manufacture of rechargeable batteries with a capacity of up to 100 kWh for the whole life cycle of an electric vehicle (290,000 km) is shown in Fig. 29. There is a significantly lower air pollution in battery production using energy from HPP, compared to the production using energy from fossil fuels (lignite)—about 140 times, 65 times in the case of electricity production from wind power plants and 19 times in the case of electricity production from PV plants. For example, to produce 75 kWh Li-ion (Ni-Co) battery, the needed electricity is 30.75 MWh. If this energy is produced from a lignite-fueled TPP, 33.8 tons of CO_2 emissions would be generated, which corresponds to 117 g/km emissions during life cycle of the electric vehicle. If renewable energy is used, CO_2 emission would be from 0.85 to 6.00 g/km depending on the energy source (HPP, wind or PV power plant).

The general opinion of many researchers is that battery recycling is not cost-effective for a number of reasons, notably the high energy consumption and waste products. Therefore, long-term recycling will be primarily geared to environmental benefits or adherence to accepted environmental laws.

The use of renewable energy during the exploitation of electric vehicles influences the CO_2 emissions through the electrical energy needed to charge their batteries. Emissions of CO_2 can be expressed by the equation

$$CO_2 = c\, E_{PE} \frac{1}{L}, \text{ g/km}, \tag{17}$$

where E_{PE} is the specific energy consumption of the BEV, Wh/km.

Figure 30 shows the possibility of reducing the CO_2 emissions during the exploitation of the electric vehicle using the energy from RES. For example, at an energy consumption of 210 Wh/km, if we charge the battery only with electricity from a TPP with lignite fuel, CO_2 emissions will be 231 g/km. If the electricity only from hydro power plants is used, the emissions will be 1.65 g/km. Respectively, use only

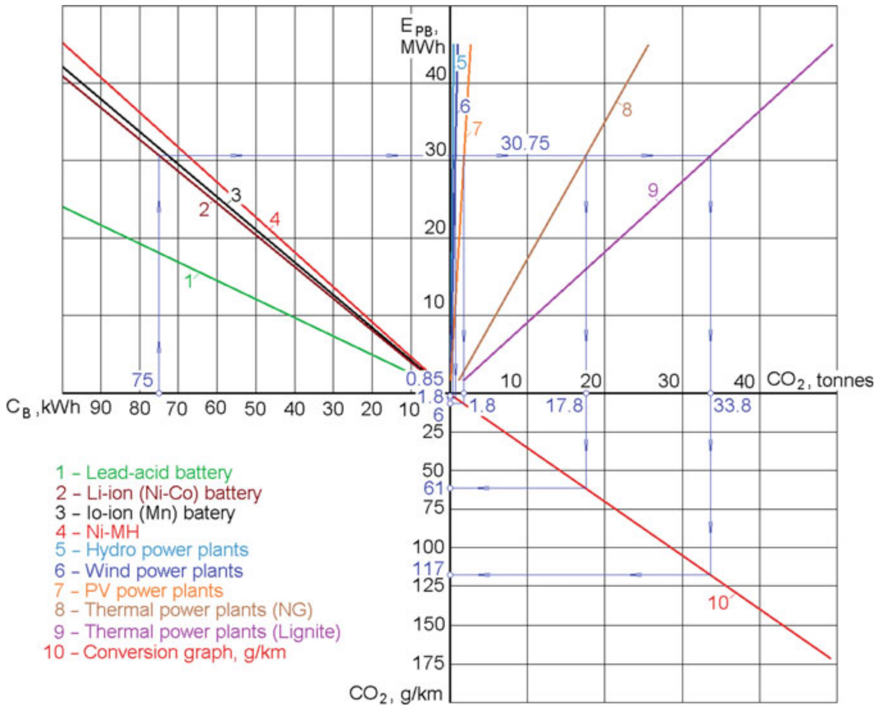


Fig. 29 Determination of CO_2 emissions from the production of different types of batteries depending on their capacity and the source of electric energy [75]

the electricity from wind power plants generates 57 g/km emissions and electricity from PV plants generates 12.18 g/km.

On the basis of (17), it is determined how much CO_2 emissions are emitted per a 1 km trip, at vehicle energy consumption of 210 Wh/km. This is illustrated on Fig. 31, using the emission factor data from Table 10. Less air pollution from electric vehicles, during their exploitation, in countries such as Austria, Sweden and Finland is mainly due to the large share of renewable energy in the energy mix, whereas in France, the main cause is the large share of nuclear energy (see Table 9).

Based on (15), (16) and (17), the CO_2 emissions can be determined for the whole life cycle of BEV as

$$CO_2 = c\left[(E_{PE} + E_{PB}\,C_B)\frac{1}{L} + 10^{-3}\,E\right], \text{g/km}. \tag{18}$$

Table 12 shows the energy consumption and the CO_2 emissions for the vehicles considered, per 1 km. All electric vehicles consume the same secondary energy of 0.309 kWh/km, which depends on the energy consumption of the electric vehicle and the efficiency of the charging station and the battery.

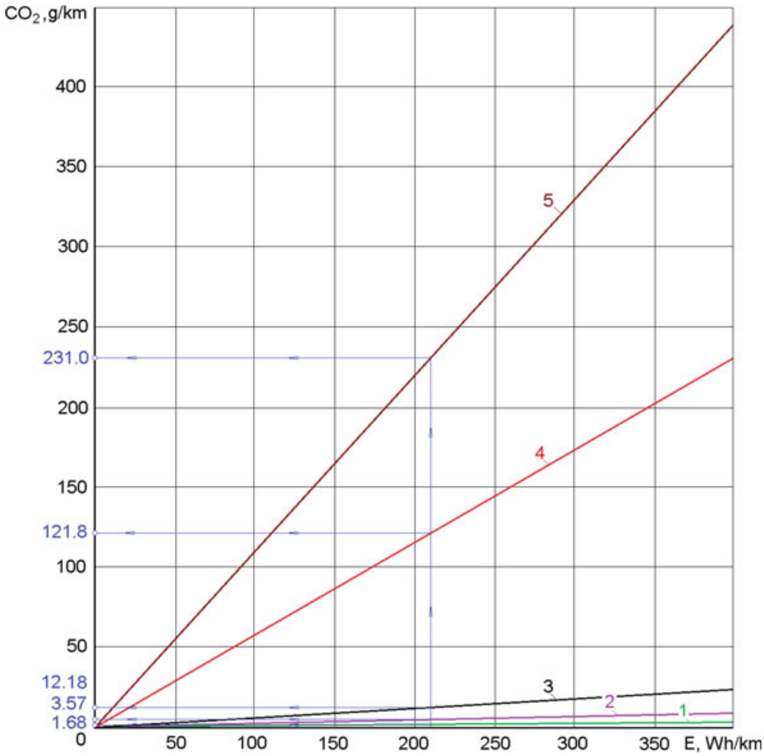


Fig. 30 Determination of CO_2 emissions, depending on the electric energy consumption of the electric vehicle, using different sources of energy for charging of its batteries [75]: 1—hydro power plant; 2—wind power plant; 3—PV power plants; 4—thermal power plants (NG); 5—thermal power plants (lignite)

The results per 1 km show once again that most efficient is BEV-3. It is obviously that the best way to increase the efficiency of electric vehicles is to change the energy mix in favor of the NPP and the energy produced by RES.

The difference in CO_2 emissions from BEV and GV depends on the sources of electricity generation. Increasing the share of electricity from RES will reduce greenhouse gas emissions in electric vehicles and their environmental performance will steadily increase. This can be seen in Fig. 26.

Including new RES to generate electricity, the energy mix of the country and the emission factor respectively change. The effect of this change in CO_2 emissions from electric vehicles can be determined from the same Fig. 26.

A comparison between life cycle energy consumption and CO_2 emissions of BEV and GV was made. From the obtained results, for the effects of replacing the conventional gasoline vehicle fleet with electric vehicles, some conclusions can be drawn.

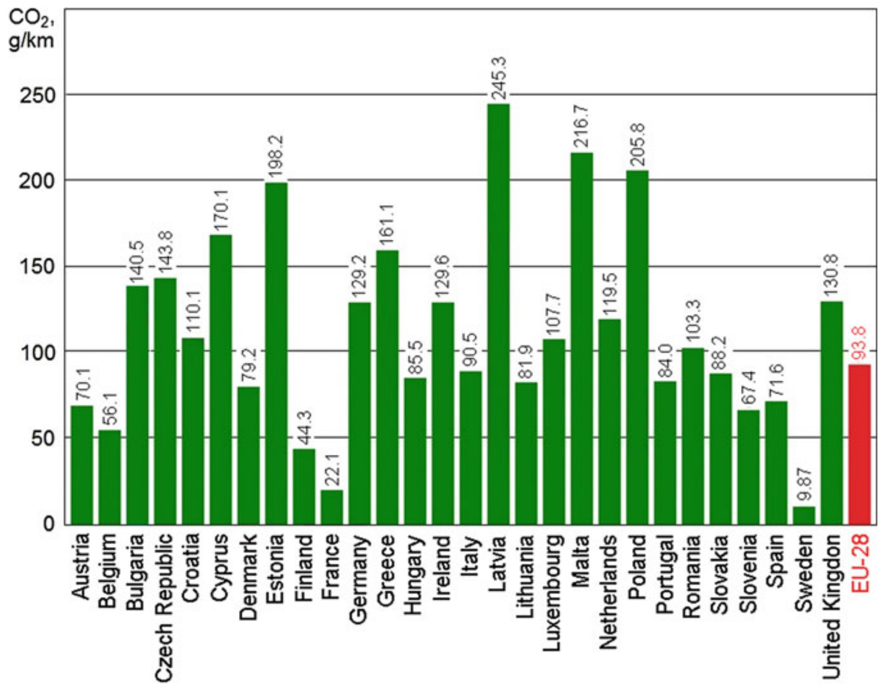


Fig. 31 Air pollution from electric vehicle exploitation depending on the emission factor of the EU-28 countries [75]

Table 12 The needed energy and generated emissions per 1 km distance for separated vehicles

Vehicle	Primary energy	Secondary energy	CO_2, g/km
	E, kWh/km		
BEV 1	1.156	0.309	207
BEV 2	1.030	0.309	138
BEV 3	0.620	0.309	5.28
BEV 4	1.272	0.309	303
GV	1.068	0.880	206

Using RES to produce electricity can reduce life cycle CO_2 emissions of the BEV up to 40 times than the respective of a gasoline GV.

The use of electricity from HPP can reduce CO_2 emissions from electric vehicles during their life cycle approximately 140 times compared to the use of electricity produced from fossil fuels (lignite), 65 times compared to the use of electric power from WPP and about 20 times when using electricity from PV plants.

The use of electricity mainly from fossil fuels leads to an increase in global warming problems due to the generation of more CO_2 emissions from BEV than GV.

At an emission factor of less than 669 g/kWh, according to the accepted conditions in this study, electric vehicles pollute the environment less than conventional vehicles. The most effective way to decrease the energy needs and CO_2 emissions for life cycle of the BEV is to change the energy mix by using more energy produced by RES and NPP.

2.3 Life Cycle Assessment of Fuel Cells Electric Vehicles

Growing towards production of FCV as an alternative of conventional vehicles, require an assessment of their advantages and disadvantages for the life cycle. FCVs, like battery electric vehicles (BEV), do not generate air pollutions during the motion process. The main difference is supply of the electric motor with electric energy. In FCV, the electricity is produced in motion, from fuel cells (FC), by continuous supply with hydrogen (H_2) and oxygen (O_2). Produced electricity is used not only for motion but also for charging the electric battery at some regimes.

The fuel cell is an energy convertor which theoretical efficiency can be up to 83% [92]. If all loses in auxiliary systems of the cell are taken into account the real efficiency of electric vehicle fuel cells is approximately 40–50%. This value is nearly as efficiency of the diesel ICE [92].

The main properties of the gasoline, natural gas and hydrogen are presented in Table 13.

The gasoline is produced at normal atmosphere conditions trough distillation of crude oil at temperature from 30 to 200 °C. The main stages of the process are shown on Fig. 33.

Table 13 Physical-mechanical properties of the regarded vehicle's fuels

	Gasoline	Natural gas	Hydrogen
Chemical formula	C_8H_{18}	CH_4	H_2
Specific burning heat, (LHV—HHV)[a], MJ/kg	43.45–46.54	45.86–50.84	119.95–141.88
Energy density, (LHV—HHV), MJ/l	33.16–34.90	(35.22–39.05) × 10^{-3}	0.1 MPa—(10.05–11.88) × 10^{-3} 35 MPa—(2.837–3.355) 70 MPa—(4.761–5.631) Liquid—(8.685–10.273)
Density at 20 °C, kg/l	0.72–0.76	0.7166 × 10^{-3}	0.1 MPa—0.0838 × 10^{-3} 35 MPa—23.65 × 10^{-3} 70 MPa—39.69 × 10^{-3} Liquid—72.41 × 10^{-3}

[a]LHV, HHV—respectively low and high limit of the value

The maximal and minimal values of the specific burning heat of coal are accepted respectively as 25.86 and 27.16 MJ/kg.

There are three basic methods for hydrogen production [59, 66]: reforming of natural gas, gasification of coal and electrolysis of water (Fig. 32). In the last decade production of H_2 from biomass increases. It is generated by the industry and farms. Electrolysis through solid oxides electrodes (SOEC) is one possibility to produce hydrogen using renewable energy sources. The properties of the basic technologies are summarized in Table 14.

Research methodology
The used LCA takes into account all processes, connected with the product (in our case fuel)—from extraction of raw material, production process, use in vehicles and it recycling (eventually) [55]. Schematic, the LCA for hydrogen and gasoline is presented on Figs. 32 and 33.

In the conducted energy analysis, the maximal value of specific burning heat (HHV) is used (Table 13). It corresponds better with real energy content of the fuel, based on the principal of energy saving.

The needed primary energy is analyzed only concerning production of H_2 and its compression up to 700 bar or its condensation. All processes connected to refining, transportation and preservation of the raw materials and fuel are not included in estimation. The same also concerns the environmental estimation.

A comparison between structure of FCV (Fig. 34) and conventional GV shows that they have one similar part of construction—chassis which includes steering system, brake system, suspension and body. Nevertheless, propulsion system and its components are very different and for its production, the spent energy and generated emissions will be different values. Usually the FCV has about 20% bigger mass.

In this study it is accepted that energy spent for producing of chassis of FCV and GV is equal and consists of 11,900 kWh [68].

For production of the FC and its management systems the spent energy is approximately 15% more than for chassis of vehicles [93]. For this reason, it can be accepted that production of the FCV use 80% more energy and generates 80% more emissions than production of a GV. Whereas 100% of GV parts can be recycled, for FC this percentage is only 75% [93, 94].

When the needed primary electric energy for vehicle production is determined, the structure of country energy mix is considered (Table 10). The efficiency of the used technologies for electricity production is also taken in consideration. [65].

The fuel consumption is determined on the basis of HHV of H_2 and gasoline, efficiency of the ICE and FC. That way, the equal energy is used for motion of the two type of vehicles with equal mass. Determination of the energy spent during exploitation of the GV, the losses concerning life cycle of the fuel are calculated and this way the effectiveness of gasoline production is evaluated as 79.6% [65, 95, 96]. Consider expected trends in development of FC production technologies a value of FC efficiency of 50% [70] is used in calculations.

The generated CO_2 emissions during the exploitation period of the two types of vehicles are determined on the basis of average fuel consumption. Evaluation of

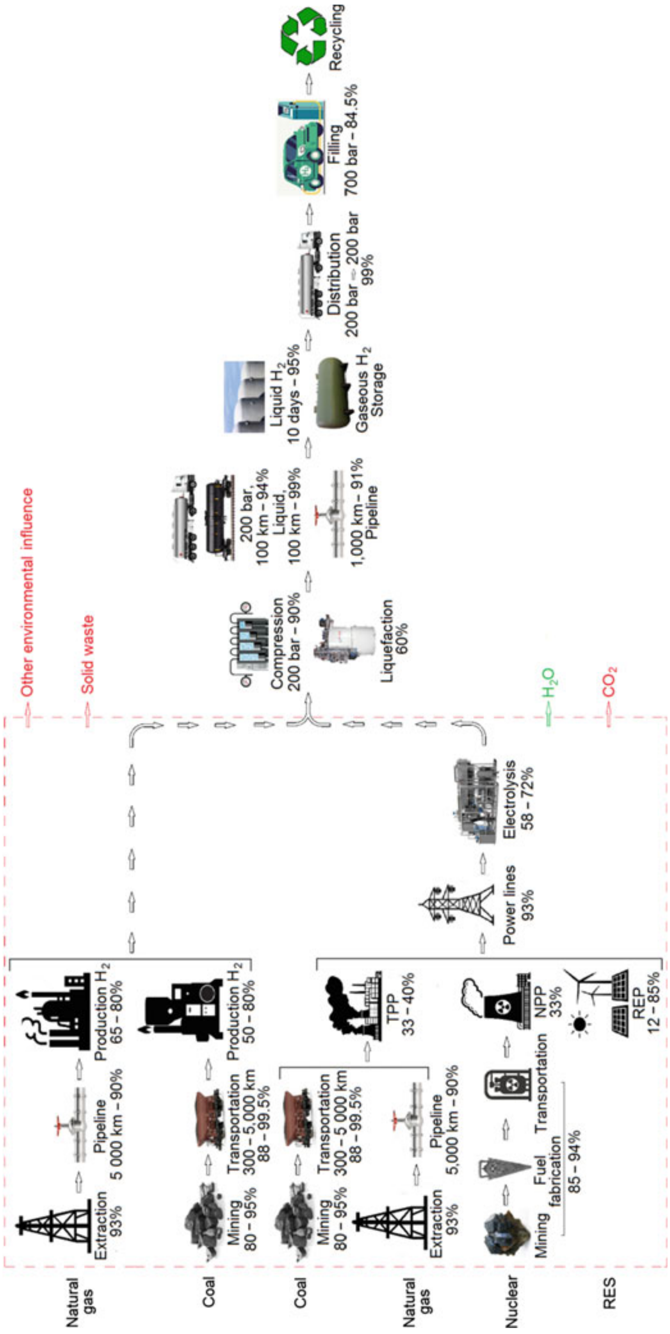


Fig. 32 LCA diagram for production and use of hydrogen in FCV [141]

Table 14 Needed resources and generated emissions for production of 1 kg H_2 using different sources and technologies [59, 66]

Method	Thermo-chemical				Electrolysis	
Raw materials	Reforming of natural gas with steam	Gasification of coal	Gasification of biomass	Reforming of biomass	PEM	SOEC
Natural gas, kWh	45.833	–	1.73	–	–	14.1
Coal, kg	–	7.8	–	–	–	–
Biomass, kg	–	–	13.5	6.54	–	–
Electricity, kWh	1.11	1.72	0.98	0.49	54.6	36.14
Water, kg	21.869	2.91	305.5	30.96	18.4	9.1
Average CO_2 emissions, kg	12.13	24.2	2.67	9.193–14.02	29.54	23.32

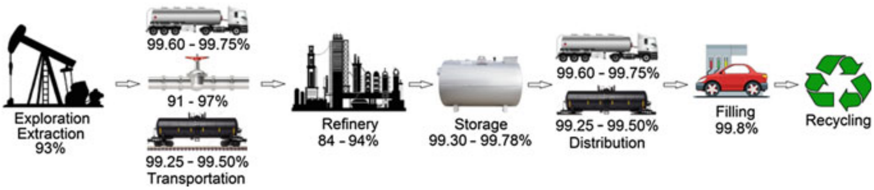


Fig. 33 LCA diagram for production and use of gasoline in GV [141]

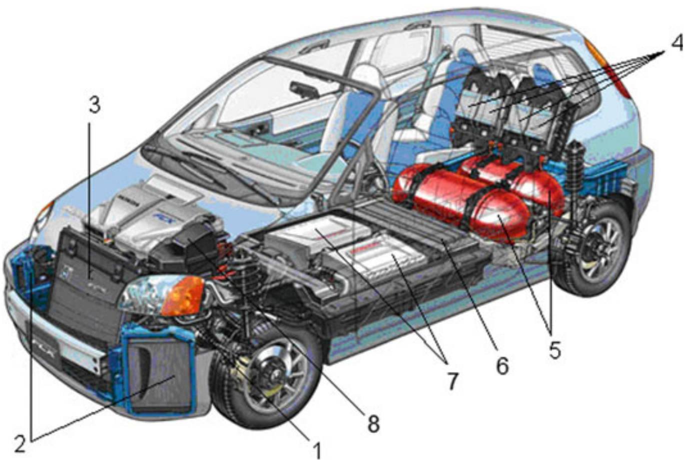


Fig. 34 Structure of a Fuel cells electric vehicle [141]: 1—electric motor; 2, 3—cooling system for transmission and FC; 4—supercapacitor; 5—reservoirs with fuel (hydrogen); 6—moisture device for FC; 7—blocs of FC; 8—power electronics

the generated CO_2 emissions during vehicles life cycle is done taking into account emissions for consumption of 1 kWh electric energy (Table 15) from companies' producer of the vehicles, at the respective voltage (HV or LV) [1].

The following assumptions are accepted: equal mass of the FCV and GV; fuel consumption of the GV—7.6 l/100 km; hydrogen consumption of the FCV, determined on the basis of average data for modern FCV—1.07 kg/100 km.

Analysis of the existing technologies for production, storage and transportation of hydrogen and gasoline

The global annual production of H_2 is over 50 million tones. The main part of whole production is from natural gas—48%, from processing of the crude oil products—30%, from coal—18% and other 4% from biomass and through electrolysis [59].

Effectiveness of hydrogen production from natural gas is between 65 and 80% [56, 63, 67, 95, 97]. The CO_2 emissions per 1 kg H_2 are 9.066–10.728 kg. On the basis of HHV values of natural gas and hydrogen (Table 13), and taking into account technological losses is evaluated that for production of 1 kg H_2 the needed natural gas is 3.17 kg. For the life cycle of FCV, production of the hydrogen will use 9840 kg natural gas and 3450 kWh electric energy. Production of 1 kg H_2 generates 12.13 kg CO_2 emissions (Table 14), or for life cycle of the FCV the mass of the emissions will consist approximately of 37,640 kg.

Effectiveness of hydrogen production from coal varies between 50 and 80% [97, 98], depending on technology and quality of used coal. The losses in production of coal are 5–20%, depending on exploitation conditions and place of the mine [82, 99], losses for transportation can reach up to 15% [100]. Hence, for life cycle of FCV, production of hydrogen from coal, a value of effectiveness of 50% can be used [95]. The mass of the CO_2 emissions consists of 24.2 kg per 1 kg H_2 [59].

Production of H_2 from biomass will have important place in the future, because it is renewable source. Effectiveness of hydrogen production through gasification of

Table 15 Main technical data of some modern FCEV

Technical indicators	Model		
	 2017 Honda Clarity	 2017 Hyundai Tucson	 2017 Toyota Mirai
Consumption of H_2, kg/100 km			
– Urban	0.914	1.295	0.942
– Inter-city	0.942	1.243	0.942
– Combined	0.928	1.268	0.942
Electric motor	PMSM, 130 kW	ASM, 100 kW	ASM, 56 kW
Battery	Li-ion, 346 V	Li-ion, 180 V	NiMH, 245 V

dry biomass (like wood, straw etc.) is into the limits of 65.7–79.1%. Generated CO_2 emissions are up to 13.5 g per 1 kg H_2. The wet waste from biomass (like sediments, organic waste etc.) can be put to gasification (effectiveness of 35.8–40.3%) or biochemical treatment (effectiveness of 29.1–36.3%) [101]. Generally, the effectiveness of hydrogen production from biomass is accepted as 65.7% [101].

Production of hydrogen through electrolysis has effectiveness of 47–82% [58, 62, 97, 102]. High values concern modern electrolysers. Without losses for transfer of the electricity (≈5%), the efficiency is 68.4%.

Alkali electrolysis is known and used since the 18th century. It is in the basis of technology and more of commercial electrolysers. The produced hydrogen is very pure, but the price is higher because of low price of petrol (used in SMR) in comparison with electricity. Low temperature polymer electrolysis membrane (PEM) and high temperature electrolysers of solid oxides (SOE) are two more effective future technologies. PEM is appropriate for production of small volumes of hydrogen. SOE electrolysers can reduce consumption of electricity using thermal cracking process [99, 103].

The use of RES for supply electrolysis [104] is very small—about 3%. The main cause is low efficiency.

With electricity from photovoltaic power plant in technology with efficiency 95% will give a total efficiency of electrolysis from 7.8 to 18% [105]. At the same technology using electricity from solar PS and Sterling motor and generator, the total efficiency can be increased to 28% [105].

Solar PS using cycle of Rankine and technology of solar tower can achieve annual efficiency of 15% and total efficiency of electrolysis—14% [105].

The solar PS with parabolic reflectors has annual efficiency of 12% and total efficiency of transformation process of solar energy into hydrogen using electrolysis—11% [105].

Transportation of the hydrogen is realized by pipes or in special tanks (as gas or as liquid) using vehicles and railway or marine transport. The cheapest method for large volumes H_2 is transportation as gas in pipes. The losses during transportation of hydrogen are significantly higher than analog losses for natural gas.

Charging of the hydrogen on FCV is made in special hydrogen stations at pressure 700 bar (70 MPa). Usually one charge is enough for a range of 400–500 km.

Compression of the hydrogen needs about 3.5 times more energy [106, 107] in comparison with natural gas at same pressure (Fig. 35).

Figure 36 shows a possibility for reducing the transport losses—if the hydrogen is liquid [106]. The transformation process of H_2 in liquid phase generates losses up to 40% [69, 106]. In analysis done below are used values for losses equal to 15.5% (from HHV) for compression up to 700 bar and 33.33% for transformation process of H_2 in liquid phase.

Transportation of H_2 in pipe generates less energy losses. Transportation of natural gas at a distance of 5000 km generates losses of 10% (Fig. 37). For H_2 transport losses are 35%, because of energy spent for supply of the compressors, placed at each 150 km (generated losses about 1.4%) [106].

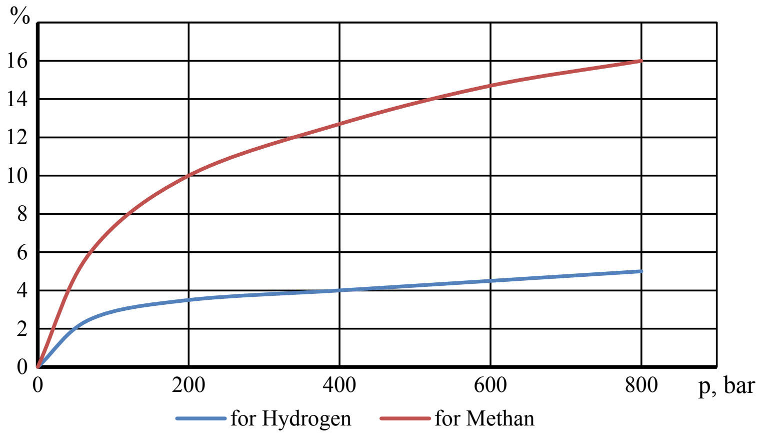


Fig. 35 Relation between energy losses for compression (in % of HHV) and pressure p [141]

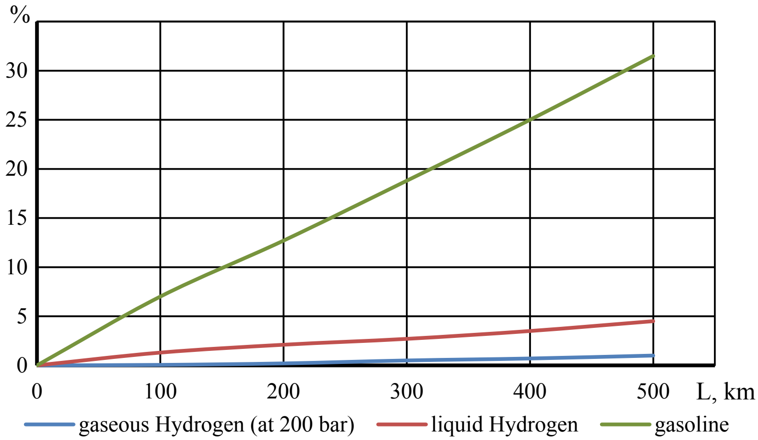


Fig. 36 Relation between energy losses for fuel transportation by vehicle (in % of HHV) and transport distance L [141]

Storage of liquid H_2 generates the highest losses—5.5 kg per day for a reservoir of 725 kg capacity, which is 0.76% per day [108]. There is a tendency in future to decrease storage losses to 5% per 10 days.

LCA for FCV and GV. Results and analysis

Using the given information above, an assessment of constant energy losses and generated emissions for FCV and GV was done. Following diagrams from Figs. 32 and 33 the two models were described—for FCV and GV. The primary energy E_{PFCV} spent for the life cycle of the FCV was evaluated by the following model

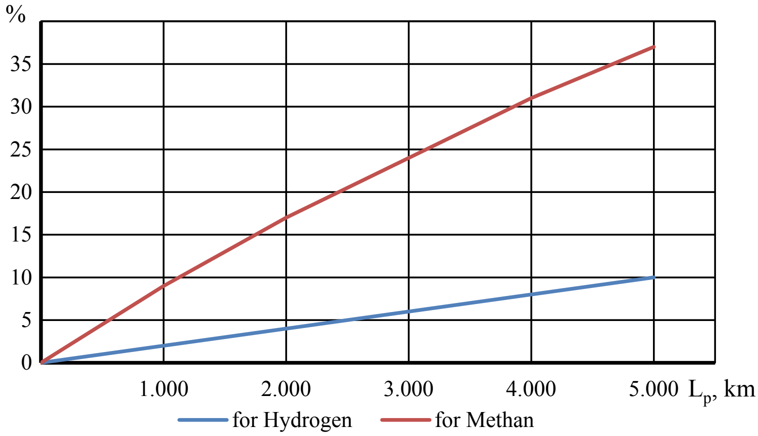


Fig. 37 Relation between energy losses for fuel transportation in pipe (in % of HHV) and transport distance LP [141]

$$E_{PFCV} = \frac{1}{\eta_T}\sum_{i=1}^{n}\frac{\alpha_i}{\eta_i}\left(E_{MV} + E_{PH_2} + E_{C(L)\mathrm{H}_2}\right), \mathrm{kWh}, \tag{19}$$

where

α_i—is the part of electricity produced in different types of power-plants (as part of whole produced energy);
η_T—efficiency of electricity transfer;
η_i—efficiency of different power-plants, including production technology and fuel transportation;
E_{MV}—energy spent for production and recycling of the vehicle, kWh;
E_{PH_2}—energy spent for production of H_2 for life cycle of FCV, kWh;
$E_{C(L)\mathrm{H}_2}$—energy spent for compression or transformation in liquid phase of H_2, kWh.

The generated emissions for FCV were evaluated by the expression

$$\mathrm{CO}_{2FCV} = c\left(E_{MV} + E_{\mathrm{PH}_2} + E_{C(L)\mathrm{H}_2}\right) 10^{-3}, \mathrm{kg}, \tag{20}$$

where c is emission factor for production of electricity, g/kWh (see last column in Table 10).

For GV used equations are:

$$E_{PGV} = \frac{1}{\eta_T}\sum_{i=1}^{n}\frac{\alpha_i}{\eta_i}(E_{MV} + E_{PG}), \mathrm{kWh}, \tag{21}$$

where E_{PG} is energy spent for production of gasoline for life cycle of GV, kWh;

$$CO_{2GV} = [c(E_{MV} + E_{PG}) + eL]10^{-3}, \text{kg}, \quad (22)$$

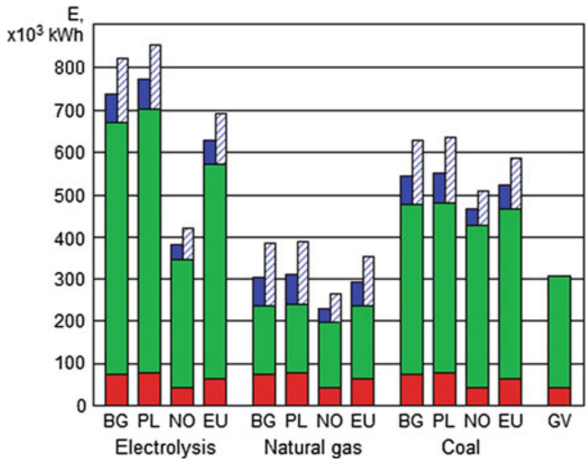
where

e—is average specific value of CO_2 emissions caused by driving, g/km (used value 180 g/km);
L—range of GV for life cycle, km (used value 290,000 km).

A LCA of FCV and GV concerning needed primary energy and emissions was done by models (19) and (20). The calculations were repeated 4 times—for conditions in Bulgaria, Poland, Norway and corresponding to energy mix of EU-28. The results are presented on Figs. 38 and 39 also in Tables 15 and 16.

The technology for production of hydrogen from natural gas is most effective by criterion of spent primary energy. Using it, at some conditions FCV can be competition of GV. The technology of production of H_2 from coal and by electrolysis, at the current stage of development, is less effective concerning primary energy for life cycle of GV vehicle. Significant use of the RES in energy mix of the country can give advantage of the FCV—for example Norway (Fig. 38).

By criterion emissions, the technology using natural gas for production of hydrogen has advantage once again. At the moment, other technologies are less ecological and their use less ecological in comparison with GV. Only in Norway, thanks to the large use of the RES in energy mix, the FCV is more ecological. Energy mix, including basically thermal PS on coal, is a factor for bigger losses of energy during life cycle of the FCV and more CO_2 emissions—for example Poland and Bulgaria (Figs. 38 and 39).



– production and recycling of the vehicles; – production of H_2 and gasoline;
– compression of H_2; – transformation to liquid H_2

Fig. 38 Primary energy, spent for life cycle of the FCV and GV [141]

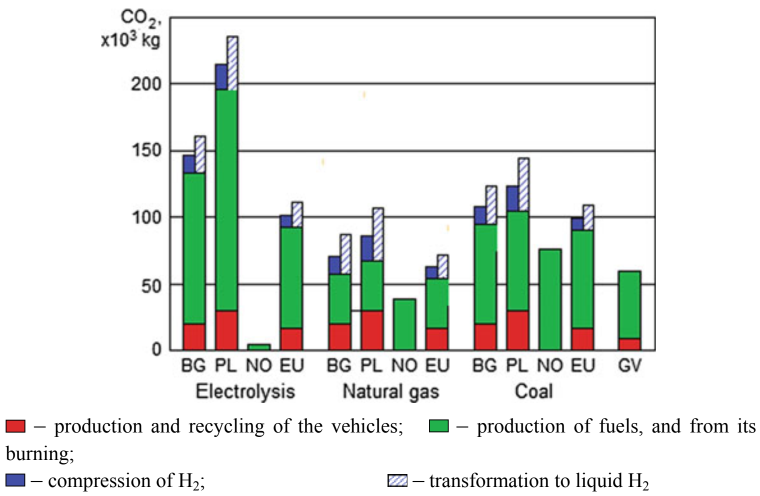


Fig. 39 CO_2 emissions generated for life cycle of the FCV and GV [141]

Table 16 Needed primary energy in kWh/km at different technologies for production of H_2

№	Country	Technology		
		Electrolysis	From natural gas	From coal
1	Bulgaria	2.567/2.833[a]	1.062/1.327	1.893/2.159
2	Poland	2.664/2.940	1.082/1.357	1.914/2.190
3	Norway	1.313/1.449	0.800/0.902	1.621/1.756
4	EC-28	2.165/2.389	1.012/1.237	1.806/2.030

[a]Values above concern compressed H_2, values below—liquid H_2

One better assessment of the three used technologies for production of hydrogen can be done on the basis of needed primary energy (Table 16) and generated emissions in CO_2 equivalent per 1 km (Table 16).

For the life cycle of the GV are spent 309,750 kWh or 1.068 kWh/km at accepted range of 290,000 km. By this criterion, FCV is competition to GV only in case of using compressed hydrogen. In Norway, FCV is more effective as it consumes less primary energy—respectively 15.5 and 25% for liquid and compressed H_2. The electrolysis is the worst of the three technologies. The energy spent for life cycle of the FCV, depending on energy mix of the country, can be over 2.5 times higher than respective for GV. For the life cycle of GV are generated 59,750 kg CO_2 emissions or 0.206 kg/km.

Results (Table 17) show that the most ecological technology is electrolysis for countries using a large part of RES in its energy mix. For example, in Norway FCV will have 16 times less emissions (Fig. 39).

Table 17 Generated CO_2 equivalent emissions in kg/km, at different technologies for production of H_2

№	Country	Technology		
		Electrolysis	From natural gas	From coal
1	Bulgaria	0.506/0.556[a]	0.243/0.294	0.373/0.423
2	Poland	0.741/0.814	0.296/0.370	0.425/0.449
3	Norway	0.013/0.014	0.133/0.134	0.262/0.263
4	EC-28	0.338/0.371	0.206/0.239	0.334/0.368

[a] Values above concern compressed H_2, values below—liquid H_2

The structure of energy mix has the most significant influence on production of hydrogen through electrolysis in countries with high level of emissions per 1 kWh electricity. Most ecological for these countries is technology for production of H_2 from natural gas. Produced and used in these countries FCV will have ecological disadvantages in comparison with GV, independent of used technology for production of hydrogen (Fig. 39).

A study of the FCV effectiveness, at different producing technologies of hydrogen (H_2) was carried out. Using Life cycle assessment, a comparison, concerning energy consumption and air pollutions for fuel cell electric vehicle and conventional gasoline vehicle was done. The influence of the energy mix and technology of production of hydrogen on spent energy and air pollution was analyzed on the basis of statistical data.

The obtained results show that the technology of hydrogen production from natural gas is most effective in countries with CO_2 emissions over 447 g per 1 kWh electricity.

The energy spent for life cycle of the FCV, depending on energy mix of the country, can be over 2.5 times higher than the respective for GV.

The most ecological technology for production of hydrogen is electrolysis for countries using a large part of renewable energy sources in its energy mix. For example, in Norway FCV will have 16 times less emissions than GV.

Positive ecological and financial effects from replacing the vehicle fleet with FCV, at the moment and in near future are not strongly proven.

The results of the present study have to be understood as one indicative simulation, which highlights positive and negative features of FCV.

2.4 Life Cycle Assessment of Vehicles, Using LPG or NG

The advantages of natural gas as a fuel for vehicles are its abundance and widespread distribution infrastructure. Its combustion produces less harmful emissions—up to a 30% reduction in GHG emissions for light commercial vehicles and up to 23% reduction for medium to heavy-duty vehicles compared to conventional vehicles [109, 110].

In [111] are evaluated the harmful emissions of flue gas and gas of light commercial vehicles. It is indicated that natural gas emits approximately 6–11% lower levels of emissions compared to gasoline throughout the life cycle of fuels.

A big part of the harmful emissions during the life cycle of natural gas is mainly a result of its leakage during the production cycle [112, 113]. In total, life cycle losses from natural gas leakage range from 0.2 to 17.3%, but the Environmental Protection Agency (EPA) regulates 1.5% losses [114, 115].

Whether natural gas used as fuel in vehicles or power plants has lower greenhouse gas emissions from the life cycle of coal and oil depends on the leakage level during its extraction and transportation, the real potential of global warming of natural gas, energy conversion effectiveness and other factors. It has been found that natural gas losses must be maintained below 3.2% in order natural gas-fired power plants to have lower life-cycle emissions than coal-fired power plants for a short period of at least 20 years. The use of natural gas in vehicles will lead to some benefits if natural gas losses are less than 1–1.6% compared to diesel and gasoline. There exist modern technologies for reducing the bigger part leaking methane, but their implementation is limited mainly by political and economic reasons [116].

Everything that has been outlined in studies so far with this regard states unclear and incomplete conclusions regarding the assessment of the impact of different types of fuels on carbon emissions through their life cycle. This is due to the different research methods with a rather wide range of variation of values of certain parameters at different stages of the life cycle.

In recent years, life cycle assessment has become a major tool in research in order to examine the entire life cycle of a product in terms of its sustainable development [55]. The evaluation covers all processes related to the functioning of a product—from the extraction of raw materials to its production, use and recycling. The results of this study should be considered as an indicative simulation to shed light on the positives and negatives aspects of different types of fuels on exhaust emissions and their impact on global warming.

For this evaluation is appropriate to use higher values of the combustion heat, since it reflects the true energy content of fuels based on the principle of energy conservation (Table 18).

The life cycle assessment of vehicles operating with different fuels usually includes impacts related to the production of raw materials, transportation, refining, distribution and fuel consumption for vehicles. Some of the process steps are excluded from the analysis due to the significantly large deviations of certain parameters. For example, transportation of fuel and constructed facilities for production, transportation and storage. Figures 40 and 41 show the general life cycle stages of different fuels, including the production and recycling of vehicles [117–122].

Vehicle carbon emissions for each type of fuel are calculated on the base of the whole life cycle, which includes emissions from the vehicle production, production of fuels and the relevant raw materials and fuel combustion through the life cycle of the vehicles.

Table 18 Physic-mechanical properties of automobile fuels

Parameters	Gasoline	Liquefied petroleum gas	Natural gas
Chemical formula	C_8H_{18}	$C_3H_8 + C_4H_{10}$	CH_4
Combustion heat, (LHV—HHV), MJ/kg	43.45–46.54	47–50	45.86–59.84 49–55[a]
Energy density, (LHV—HHV), MJ/l	31.16–34.90	23–26	$(35.22–39.05) \times 10^3$
Relative density at 20 °C, kg/l	0.72–0.76	0.50–0.58	0.7166×10^{-3} 0.4218[a]
Temperature at self-flaming, °C	228–471	365–470	632
Octane number (RON)	91–98	94–112	135
Molecular mass, g/mol	102–107	44–58	16.04
Stoichiometric ratio	14.96	15.4	17.2
Boiling point, °C	80–225	−42 to −0.5	−161.58

[a]Liquid phase

Propane-butane is considered as a combined product of fuels derived from petrol or natural gas, which is a ground for distribution of the separate emissions during the production of natural gas and refining of crude oil.

The impact of the natural gas on the global warming is accepted a value of 25, according to the evaluation of IPCC—Intergovernmental Panel on Climate Change with global warming potential (GWP) [123].

Natural gas (NG)

Derived from terrestrial fields, natural gas is a mixture of several gases and water. As a fuel in vehicles, it consists mainly of methane. Although the derived from the fields natural gas contains mainly methane, it may also contain ethane, propane, butane, water vapor, hydrogen sulphide, carbon dioxide, nitrogen, helium and sand. Many of these components need to be removed during processing in order to increase their efficiency in transportation, especially through gas pipelines.

Natural gas containing 98% methane, on liquefaction, occupies 0.17% of the volume of the same amount in the gaseous state.

The liquefaction process involves the purification by separation of certain components such as dust, carbon dioxide, hydrogen sulphide, helium, water and heavy hydrocarbons, which would cause difficulties in the conversion of the gas to liquid. The cooling temperature is approximately—162 °C. The energy density of liquefied natural gas is 2.4 times higher than that of compressed gas.

It is lighter than air and flies into the air when released into the atmosphere. Compared to other types of internal combustion engine fuels, natural gas has the highest combustion resistance. Its octane number is between 105 and 110 units, which allows to increase the degree of compression of the ICE and to improve their

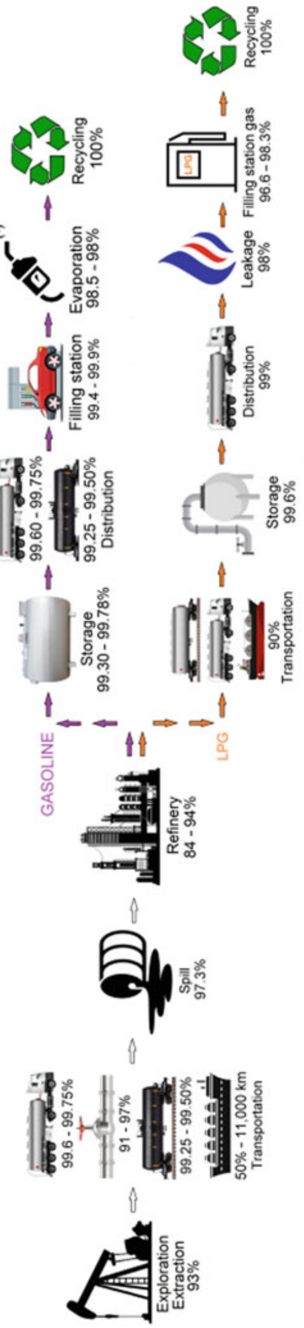


Fig. 40 Life cycle stages in gasoline and LPG production [142]

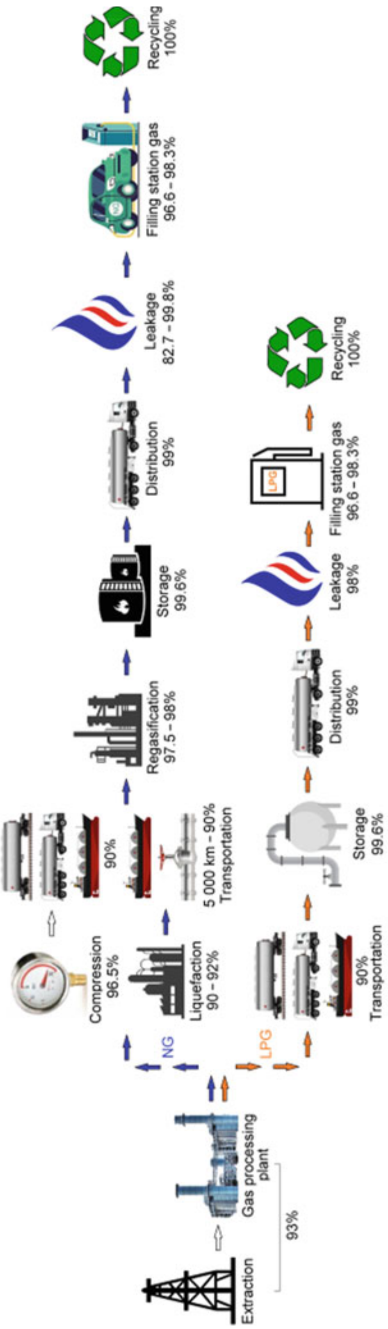


Fig. 41 Life cycle stages in NG and LPG production [142]

fuel economy. It burns more completely when mixed with air due to their uniform aggregate states.

In gasoline engines, the natural gas can replace 100% the gasoline.

Together with the extracted gas, the renewable natural gas (RNG) finds application. It is made from organic raw materials (from agriculture, food industry and waste), also known as bio-methane. It is chemically identical to extracted gas, but produces far less greenhouse gas emissions when burned. Mixing relatively small amounts of RNG with extracted gas provides a reduction in life cycle greenhouse gas emissions.

The main disadvantage of natural gas as an ICE fuel is its low volumetric energy concentration. For this reason, it is necessary to provide sufficient fuel, which can be realized in the following ways:

– by compression to high pressure up to 20–22 MPa;
– by liquefying the natural gas at—162 °C;
– by obtaining methanol from natural gas.

The broadest application is found in the first way-compression up to 20–22 MPa in special containers made of alloy steel or light alloys with reinforced construction of metal threads.

Liquefied petroleum gas (LPG)
LPG vehicles use the following combustion systems:

– evaporator and mixer conversion system;
– gas injection system.

The first system has dominated for decades and is still widely used. These are so called ordinary gas appliances. The second system has been the most popular in recent years due to better control of the combustion process in the engine cylinders.

Liquefied Petroleum Gas is a combined product of natural gas production and refining of crude oil. Propane-butane is released from crude oil and natural gas during extraction. Natural gas contains mainly methane but also other substances, such as heavier hydrocarbons, including C_3H_8 and C_4H_{10}. Its preparation for transport requires the removal of the LPG fraction—degassing. Additional LPG quantities are also obtained to stabilize crude oil as it is extracted as part of the preparation of oil for transportation. Globally, about 60% of propane-butane is estimated to be produced in this way. The remaining 40% of propane-butane is produced during the refining of oil. Depending on the type of crude oil, it may contain from 1 to 4% fraction of propane-butane [124].

LPG is gaseous at normal temperatures and atmosphere pressure, and it is delivered liquefied under pressure in steel bottles. The ratio of volumes of evaporated gas to liquefied gas varies depending on composition, pressure and temperature, but is usually around 250:1. The pressure at which the LPG liquefies (saturated vapor pressure) also varies with composition and temperature, being about 0.22 MPa for pure butane at 20 °C, and about 2.2 MPa for pure propane at 55 °C.

Propane-butane will not create an environmental hazard if released as liquid or vapor in water or soil. If spilled in large quantities, the only environmental damage that can occur is the freezing of any organism or plant life in the immediate vicinity. The long-term effects of propane-butane gas spills have not yet been reported, even in large quantities. Only major damage can occur if, after the spill, the LPG is ignited.

The main difference between conventional fuels and LPG is storage—it is gaseous at room temperature and atmospheric pressure. Thus, storage tanks are required in both gas stations and vehicles. Due to their pressure-resistant design, LPG tanks are a little more expensive, heavier, and require more space than gasoline or diesel tanks.

Mathematical model for the Life-cycle assessment of vehicles using gasoline, natural gas and LPG in relation to the primary energy

Primary energy for the life cycle of vehicles using different fuels can be represented by the following mathematical model

$$E_P = \frac{1}{\eta_T} \sum_{i=1}^{n} \frac{\alpha_i}{\eta_i} \left(E_{MV} + E_{PF} + E_{C(L)F} + E_{L(E)} \right), \text{kWh}, \tag{23}$$

where

α_i—is percentage of electricity, produced in different power stations referred to the total produced energy;
η_T—efficiency upon electricity transferring;
η_i—efficiency of power stations, taking into account the cycle of production and transportation of their fuels;
E_{MV}—energy necessary for production and recycling of vehicles, kWh;
E_{PF}—energy necessary for production of the fuels, kWh;
$E_{C(L)F}$—energy necessary for compressing or liquefaction of fuels, kWh;
$E_{L(E)}$—energy lost due to leakage or evaporation of fuel, kWh.

Mathematical model for the life-cycle assessment of vehicles using gasoline, natural gas and LPG concerning carbon dioxide

Generated CO_2 emissions for the life cycle of fuels and vehicles can be represented by the following mathematical model

$$\begin{aligned} CO_2 = {} & cE_{MV} + 10^{-2}c(1 - \eta_F)k_F QL + 10^{-2}c_F k_F QL + c_{GWP} Q_L = cE_{MV} \\ & + 10^{-2}k_F QL[c(1 - \eta_F) + c_F] + c_{GWP} Q_L, \text{kg}, \end{aligned} \tag{24}$$

where

c—is the Emission factor in electricity production, kg CO_2/kWh;
η_F—efficiency of fuel production;
k_F—calorific value of the fuel, kWh/kg or kWh/l;
Q—fuel consumption, l/100 km or kg/100 km;

L—vehicle range for life cycle, km;
c_F—Emission factor during fuel burning, kg CO_2/kWh;
c_{GWP}—potential of global warming;
Q_L—leaked fuel, kg.

In the study, it was agreed that the chassis of the vehicle will consume 11,900 kWh [117]. Overall, the life cycle of a gasoline vehicle manufactured and powered in Bulgaria requires approximately 309,750 kWh of primary energy. About 86.5% of the life cycle energy is spent on movement. This percentage depends on the energy of the vehicle production in the respective country and the latter depends on the energy mix. Operational energy varies slightly across countries and is largely dependent on losses in the fuel production process. Other stages of the GV life cycle, such as vehicle production and parts repair, production transport, etc., consume less energy—13.5% of the life cycle or approximately 42,000 kWh.

The consumption of natural gas with an equivalent amount of energy corresponding to 7.6 l/100 km gasoline is 4.43 kg/100 km. Totally 12,847 kg will be consumed throughout the life cycle. With an emission factor of 183.96 g/kWh, a total of 39,280 kg of CO_2 emissions will be emitted during the operation of the vehicle.

The LPG consumption of the equivalent amount of 7.6 l/100 km gasoline is 10.2 l/100 km. 29,580 L of LPG have been consumed through the entire life cycle. Assuming a fuel emission factor of 214.48 g/kWh, a total CO_2 emission over the life cycle of 45,820 kg is generated.

Natural gas produces a variable and uncertain part of greenhouse gas emissions due to the leakage of methane into the atmosphere over its life cycle. In [115] stated (based on 26 publications for the period 2012–2015) that the losses of methane from leakage into the atmosphere varied too wide (from 0.2 to 17.3%). Higher values probably are result from wider confidence intervals in the study. However, the Environmental Protection Agency (EPA) concludes that the rate of loss of gas leakage for the United States is 1.5%. Therefore, the impact of these losses on global warming for the lifecycle of a vehicle with CO_2 potential for warming the atmosphere 25, according to an Intergovernmental Panel on Climate Change (IPCC) assessment report, would increase CO_2 emissions by 4820 kg CO_2 emissions.

A gasoline vehicle 4 produced and used in Bulgaria needs 309,750 primary energy for its life cycle (Fig. 42a). Approximately 86.5% from the life cycle energy is spent in movement. This percentage depends on the energy on the energy for production of the vehicle in the according county which itself depends on the energy mix.

Movement energy varies slightly in different countries and depends mainly on losses in the fuel production process. Other stages of the life cycle of a gasoline vehicle, such as vehicle production and parts repair, production transport, etc., consume less energy—13.5% of the life cycle or about 42,000 kWh. For vehicles 3 produced and operated in Bulgaria using natural gas fuel, the primary energy is in the range of 285,690 to 295,310 kWh, depending on the natural state of the natural gas—compressed or liquefied. For the vehicle 2 produced and operated with energy mix EU-28, primary energy would range from 274,920 to 283,030 kWh, less by 3.9–4.4%. For LPG fueled vehicle 1, produced and operated in Bulgaria, the primary

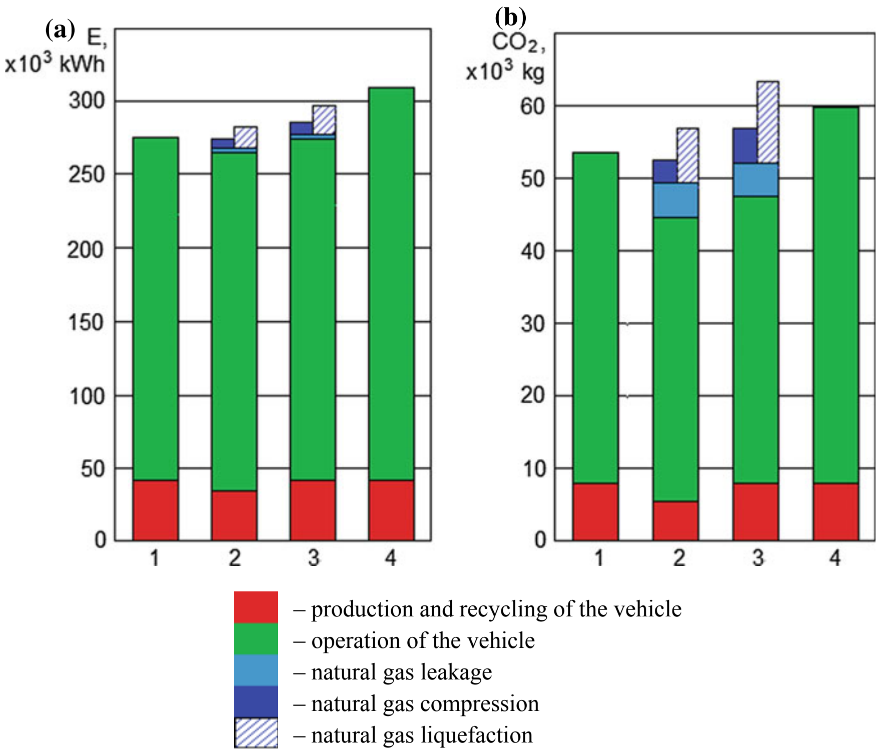


Fig. 42 Life-cycle of primary energy (**a**) and CO_2 emissions (**b**) of vehicles using different fuels [142]: 1—vehicle produced and operated in Bulgaria, using LPG; 2—vehicle produced and operated with energy mix EU-28, using NG fuel; 3—vehicle produced and operated in Bulgaria, using NG; 4—vehicle produced and operated in Bulgaria, using gasoline

energy for its life cycle is 274,390 kWh. The difference in the primary energy of vehicles using different fuels is due to the different energy costs for fuel production and the average mix in electricity production.

The greenhouse gas emissions (CO_2 equivalent) generated throughout the life cycle of conventional gasoline-fueled vehicles produced and operated in Bulgaria is 59,750 kg (Fig. 42b). Under the accepted terms of life cycle assessment for different European countries, these emissions would fluctuate around this value depending on the fuel production efficiency and energy mix of the country.

The total CO_2 emissions for the vehicles produced and operated in Bulgaria using CNG are 57,060 kg, and using LNG—63,490 kg. For the same vehicle with average emission factor of 447 g/kWh are the following: when using CNG—52,770 kg and with LNG—57,070 kg. The emission of natural gas into the atmosphere and its emissions upon liquefaction have a significant influence on these emissions.

As a percentage, the emissions during operation are as follows: 12% of CO_2 emissions from natural gas leakage into the atmosphere and 19–21% in case of

Table 19 Energy and CO_2 emissions per 1 km

Vehicles	E, kWh/km	CO_2, g/km
1	0.946	186
2	0.948–0.976	182–197
3	0.985–1.018	197–219
4	1.068	206

liquefaction. The latter depends mainly on the Emission factor in the production of electricity. The possibility of reducing these emissions is the use of renewable energy.

The life-cycle CO_2 emissions when using LPG are 53,780 kg which is 10% less than conventional vehicle. Table 19 shows figure results for energy costs and CO_2 emissions for the above-indicated vehicles referred to a road unit—1 km.

Based on the research the following conclusions could be made. With regard to the primary energy required for the production of vehicles and related fuels, gasoline-fueled vehicles are the most energy-intensive, approximately 11–12% larger than propane-butane fuel vehicles. This difference appear due to the technology of production of different fuels and the energy mix of the countries where these vehicles are produced and operated.

Vehicles using propane-butane fuel are the most efficient in terms of carbon emissions—186 g/km.

The production and operation of natural gas are in relation to its leakage into the atmosphere, which accounts to 12% of life cycle emissions under the accepted test conditions. It generates additionally few emissions from its compression and liquefaction, which in fact diminishes greatly its advantages as an environmental fuel.

The harmful emissions of natural gas fueled vehicles can be reduced to a large degree by improving the technologies of production, transportation and storage of natural gas with a significant increase in the share of renewable energy in the country's energy mix.

2.5 Comparative Analysis of Air Pollutions of Other Types of Eco-Vehicles

The vehicles, using flexible fuel mix of gasoline and ethanol, can work only with gasoline or any mix of gasoline and ethanol up to 85%. The title of different mixes come from proportion of two fuels—for example E85 is mix of 15% gasoline and 85% ethanol. The structure of the vehicle is the same as classic gasoline with ignition.

The ethanol is an alcohol fuel, which use cause a decreasing of emissions. According [125] decreasing of GHG from 4 to 8% is possible at mix E10. Use of the E85 decreases GHG up to 80%. Usually, in the studies, the spent energy for agriculture works and also used production technologies of the ethanol are not taking into account.

The main advantages of the ethanol as fuel for ICE are:

- better ecological properties;
- higher Octane number than gasoline;
- burning process do not generate PM;
- significant modification of the ICE is not need.

The analysis of data, given in Table 20, show that use the mix E85 in different models increase the fuel consumption with approximately 26%, but decreases CO_2 emissions with 8.6%.

Vehicles using mix of diesel fuels can work only with diesel oil or with mix of diesel oil and bio-diesel oil. A system called "B-factor" is used to indicate the proportion of two fuels. The pure bio-diesel fuel is B 100, mix from 20% bio-diesel and 80% diesel oil is indicated as B 20. Most used mixes are B 5 and B 20.

The structure of the vehicle is the same as a classic diesel vehicle.

Use the B 20 decreases CH with 13% and CO with more than 7% [126].

Bio-fuels production has a negative energy profit [126, 127]. For example, production of the ethanol from corn consume up to 46% more energy than ethanol can realize in burning process. Production of bio-diesel from rape and soya—respectively 58% and 63%. Independent of this, to produce big volume of bio-fuels needs of changing the purpose of large areas of land. There is a negative influence of the energy agricultures on the soil. There is a big consumption of water for pouring. Use the nitrogen fertilizer increases global GHG effect.

Due to production of bio-fuels the tropical forests are destroyed and the soils are conversed to agricultural. There are many positive and negative effects from production of bio-fuels [126, 128–130]. It is needed to take into account so-called "indirect emissions" in assessment of efficiency of bio-fuel use. The production of fuels from foods put on table the global problem of feeding of some people.

Dedicated vehicles Dedicated vehicles are specifically designed to use natural gas (CNG—compressed natural gas) as fuel. Natural gas vehicles (NGVs) are increasingly improving their safety performance. When traveling long distances, it is preferable to use liquefied natural gas (LNG). In the world, more than 22 million vehicles run on natural gas, as 10% of them in Europe. The structure of a dedicated natural gas vehicle is shown in Figs. 43 and 44.

Bi-fuel vehicles with the ability to switch engine performance from one type fuel to the other These vehicles use two types of fuels. One is gasoline or diesel and the other is natural gas, liquefied petroleum gas (LPG) also called propane-butane or hydrogen. Both fuels are stored in separate tanks and can be switched from one to the other, either manually or automatically (Fig. 45).

Dual fuel vehicles as one of the fuels is used for improvement of combustion process. The use of two types for improving the combustion process is of particular use in trucks [131, 132]. They have natural gas fuel systems but use diesel to improve

Table 20 Fuel consumption and generated CO_2 emissions of some models vehicle using gasoline and mix E85 [144]

Vehicle	 2016 Ford Focus FWD FFV, 2.0 L, Automatic (AM6)	 2016 Ford Focus FWD FFV, 2.0 L, Manual 5-spd	 2016 Mercedes-Benz CLA250 4matic, 2.0 L, AM7, Turbo	 2016 Chevrolet Equinox FWD 2.4 L, Autom. 6-spd
Fuel consumption gasoline, l/100 km				
– Urban cycle	8.71	9.06	9.8	10.69
– Inter-city cycle	6.03	6.53	7.35	7.59
– Combined	7.59	8.11	8.71	9.05
Emissions CO_2, g/km	177	190	202	216
Fuel consumption mix E85, l/100 km				
– Urban cycle	11.76	12.38	13.84	15.68
– Inter-city cycle	8.4	9.05	10.23	11.2
– Combined	10.23	10.69	11.76	13.84
Emissions CO_2, g/km	168	179	200	223

(continued)

Table 20 (continued)

Vehicle	 2016 Audi A4 Quattro 2.0 L, Autom. (S8), Turbo	 2016 Jeep Renegade 2WD, 2.4 L, Autom. 9-spd	 2016 Jeep Cherokee 4WD, 2.4 L, Automatic 9-spd	 2016 Chevrolet Equinox AWD 2.4 L, Autom. 6-spd
Fuel consumption gasoline, l/100 km				
– Urban cycle	11.2	10.69	11.2	11.76
– Inter-city cycle	7.84	7.84	8.4	8.4
– Combined	9.8	9.41	10.23	10.27
Emissions CO_2, g/km	226	222	235	237
Fuel consumption mix E85, l/100 km				
– Urban cycle	15.68	14.7	16.8	16.8
– Inter-city cycle	10.69	10.23	11.2	11.76
– Combined	13.08	12.38	13.84	13.84
Emissions CO_2, g/km	217	203	227	237

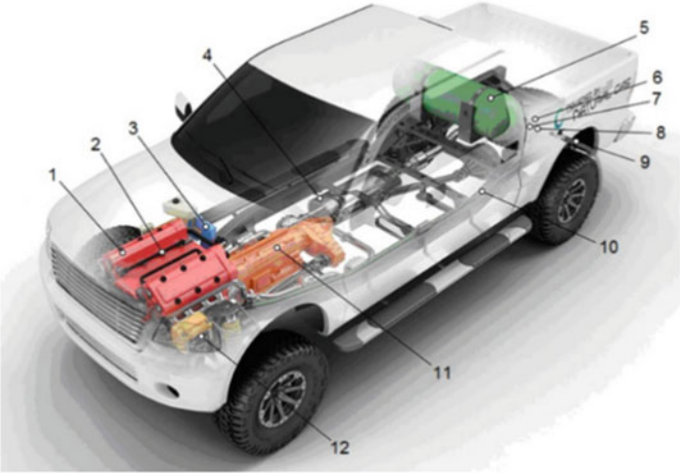


Fig. 43 Structure of a dedicated vehicle specially designed to work with CNG: 1—ICE; 2—fuel injection system; 3—electronic control module; 4—exhausting system; 5—fuel container; 6—manual switch on and off of fuel; 7—high pressure regulator; 8—filter; 9—fuel feeding; 10—fuel pipeline; 11—transmission; 12—battery

Fig. 44 Structure of a dedicated truck specially designed to work with LNG: 1—fuel injection system; 2—ICE; 3—electronic control module; 4—battery; 5—exhausting system; 6—fuel filter; 7—fuel container; 8—transmission; 9—fuel pipeline

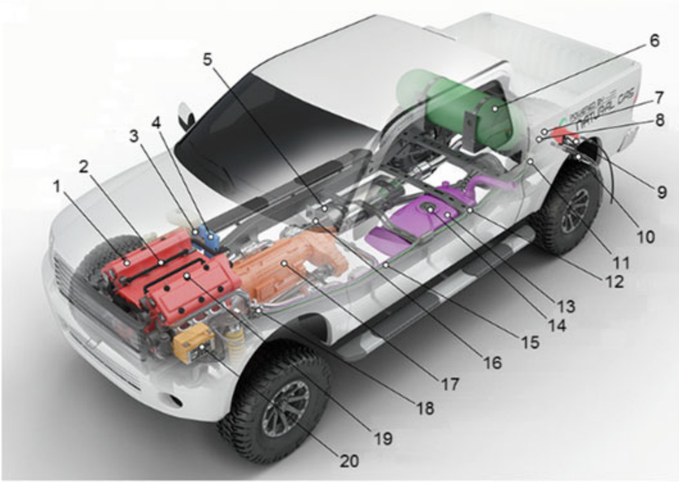


Fig. 45 Structure of Bi-fuel vehicles with the ability to switch engine performance from one type fuel to the other: 1—ICE; 2—injection system (natural gas); 3—electronic control module (gasoline); 4—Electronic control module (natural gas); 5—exhausting system; 6—natural gas container; 7—manual switch on and off of fuel; 8—high pressure regulator; 9—fuel feeding (gasoline); 10—fuel feeding (natural gas); 11—fuel filter (natural gas); 12—fuel pipeline (natural gas); 13—fuel tank (gasoline); 14—fuel pump (gasoline); 15—fuel pipeline (gasoline); 16—fuel selection switch; 17—transmission; 18—sensor (natural gas); 19—injection system (gasoline); 20—battery

their combustion process. When running both fuels simultaneously, natural gas is introduced at low pressure and mixed with the intake air. Diesel is injected directly into the combustion chamber at the end of the compression stroke and used to ignite a weak mixture of natural gas and air.

This improves engine performance and increases the efficiency of using natural gas compared to traditional natural gas-powered engines. Because air and natural gas are pre-mixed in the cylinder, these engines have many similarities with spark ignition. Typically, both fuels are used at a 60/40% ratio in favour of natural gas. Higher ratios are only possible through structural improvements to the engine. If necessary, these engines can only run on diesel.

In many cases, LNG is used as a fuel (due to its higher energy density than CNG), especially suitable for 7 and 8 class trucks (Heavy trucks) with own mass exceeding 11,794 kg for long-distance freight.

2.6 Life Cycle Assessment of Compressed Air Vehicles

The bigger part of vehicles consumes fossil fuels, which creates serious ecological air pollution with CO_2 emissions and fine dust particles. With this regard, a lot of automotive companies develop alternative and more ecological methods for vehicle propulsion. One of these alternatives is the use of compressed air for vehicle propulsion [133–139].

Theoretically, the use of compressed air as an energy source for the vehicles has some big advantages—the air is everywhere around us. However, practically it is much more complicated mainly due to the energy necessity for compressing and storing of the compressed air.

This is the main reason that limits their use as vehicles. The use of compressed air energy has long been used in various applications, but gained popularity after French companies such as Motor Development International (MDI) developed a compressed air vehicle. This popularity is due to certain advantages in the production and operation of these vehicles, namely:

- their overall efficiency is almost twice as high as the vehicles with internal combustion engines (engines) and may reach over 70%;
- the engine does not need special maintenance;
- the energy conversion process itself can be used to cool the passenger compartment, which is a great advantage when operating in warm countries;
- the cost of producing vehicles is less than conventional vehicles;
- there are possibilities for regeneration of energy in the case of delayed movement or stopping of the vehicle;
- hybrid systems using compressed air energy are cheaper, have less mass than hybrid electric systems, and significantly increase the efficiency of compressed air energy use compared to that used in CAVs.

This work will evaluate the life cycle of a CAV without using additional systems (air heating or energy recovery) to increase the mileage with a single tank charge.

The life cycle study was done based on the indicated stages (Fig. 46)—generation of electricity with appropriate sub-stages, transmission of electricity to compressed air charging stations, compressed air thinning and vehicle recycling. These lifecycle stages are similar to the lifecycle stages of electric vehicles. The difference is that electricity is used to compress air and, in electric vehicles, to charge the battery.

Compressed air has the lowest energy density of all other energy sources in vehicles (Fig. 47) [138]. Compared to gasoline, its energy density is about 200 times lower, and compared to natural gas—about 67 times (at a pressure of compressed air and natural gas 300 bar). When compared to the energy density of the rechargeable batteries, the following is obtained: about 8 times less energy density than that of the lithium-ion batteries.

With respect to the operation of a compressed air engine, an average efficiency of 39.7% can be assumed, which is 8.5% less than the maximum possible [138].

An essential point in the life cycle of these vehicles is the overall efficiency of the compressed air unit, according to [138], 53% can be assumed.

The mass of the compressed air vehicle is the smallest compared to other vehicles. This has a significant impact on energy consumption during operation. This energy can be compared to modern electric vehicles using lithium-ion batteries (see Fig. 47).

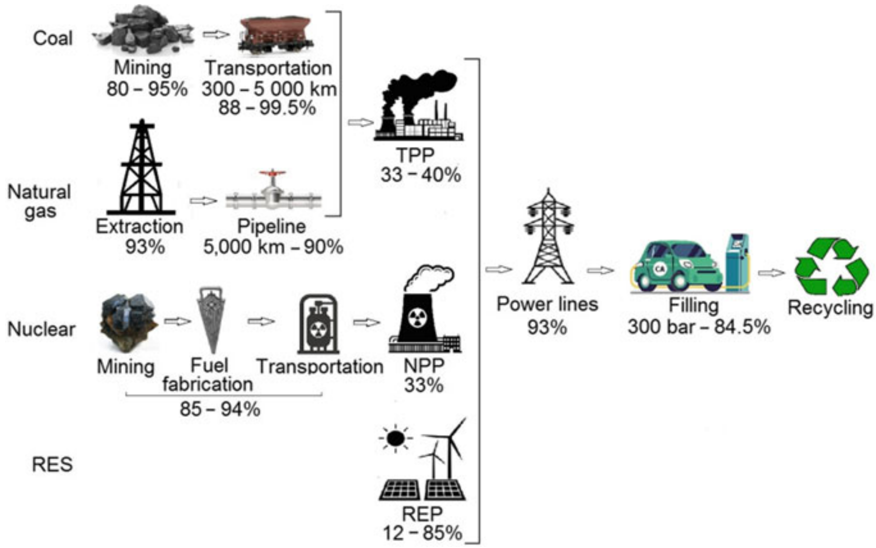


Fig. 46 Life cycle stages of the vehicles, using compressed air [143]

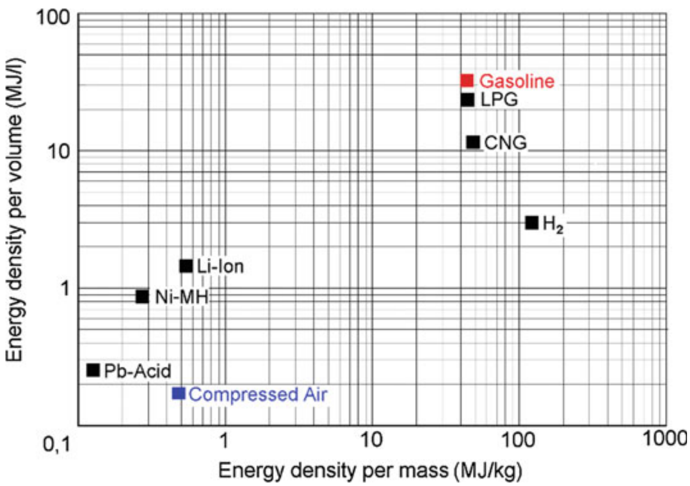


Fig. 47 Comparison of the energy parameters of different energy sources in transport vehicles [143]

The energy density of the compressed air system can be significantly increased if the air is heated (on board) before expansion.

Let analyze a tank for compressed air storing $V_2 = 300$ l with maximum pressure $p_2 = 300$ bar. According to Eq. (25) in an isothermal process, under the assumed conditions, it is necessary to compress the volume of air approximately $V_1 = 90{,}000$ l or 90 m^3. The work required to realize this pressure at this volume is approximately 14 kWh (51 MJ).

$$E_T = 0.0278\, p_1\, V_1 \ln \frac{p_2}{p_1}, \text{kWh}, \tag{25}$$

where

p_1—is standard atmospheric pressure (1 bar);
V_1—volume of compressed air, m^3;
p_2—maximum air pressure in the tank, bar.

Practically the real processes differ from the isometric ones (a process at which the temperature remains constant) and most often they run in an adiabatic process (a process where there is no exchange of heat), with a coefficient n = 1.4. The energy consumed in this process is 55 kWh (198 MJ).

$$E_{com} = 0.0278 \frac{p_1\, V_1}{n-1}\left[\left(\frac{V_1}{V_2}\right)^{n-1} - 1\right], \text{kWh}. \tag{26}$$

The efficiency of this process based on dependencies (25) and (26) is approximately 26%.

At n = 1.2 the energy spent is 27 kWh or approximately 94 MJ. The effectiveness of the process grows at 53%.

Even at high pressure, compressed air carries much less energy than other sources of energy for transport, including liquid and gaseous fuels as well as rechargeable batteries. Compressed air retains only 0.5% (Fig. 47) from gasoline energy and 1.5% from the energy of compressed natural gas (CNG) 6% of the energy density of hydrogen (H_2). By analogy, the energy density of compressed air is lower than the energy density of various types of rechargeable batteries: 67% less energy density than lead batteries (Pb-acid); 20% less energy density compared to Nickel Metal Hydride (Ni-MH) batteries and only 12% less energy density of lithium batteries (Li-Ion). This comparison is based on the energy density of compressed air, CNG and H_2 at a pressure of 300 bar.

Mathematical models defining the primary energy spent for the whole life cycle of vehicles are:

– for conventional vehicle;

$$E_{PGV} = \frac{1}{\eta_T} \sum_{i=1}^{n} \frac{\alpha_i}{\eta_i} \left(E_{MV} + E_{PF} + E_{L(E)}\right), \text{kWh} \tag{27}$$

– for the vehicle, using compressed air;

$$E_{PCAV} = \frac{1}{\eta_T} \sum_{i=1}^{n} \frac{\alpha_i}{\eta_i} (E_{MV} + E_C), \text{kWh}, , \tag{28}$$

where

α_i—is the percentage of the electricity, produced by different power plants referred to the total produced energy;
η_T—efficiency of electricity transfer;
η_i—efficiency of power stations, taking into account the cycle of production and transportation of their fuels;
E_{MV}—energy necessary for production and recycling of vehicles, kWh;
E_{PF}—energy necessary for production of the fuels, kWh;
$E_{L(E)}$—energy lost due to leakage or evaporation of fuel, kWh;
E_C—energy necessary for air compression, kWh.

Mathematical models defining the harmful emissions referred to carbon dioxide are:

– for conventional vehicles;

$$CO_{2GV} = cE_{MV} + 10^{-2}c(1 - \eta_F)k_F QL + 10^{-2}c_F k_F QL = cE_{MV} + 10^{-2}k_F QL[c(1 - \eta_F) + c_F],\ \text{kg} \quad (29)$$

– for vehicle, using compressed air;

$$CO_{2CAV} = c(E_{MV} + E_C), \text{kg}, \quad (30)$$

where

c —is the emission factor upon electricity production, kg CO_2/kWh;
η_F—efficiency fuel production process;
k_F—caloric value of the fuel, kWh/l;
Q—fuel consumption, l/100 km;
L—vehicle range for life cycle, km;
c_F—emission factor during fuel burning, kg CO_2/kWh.

Results received based on (28)–(30) are shown in Fig. 48. The primary energy spent throughout the whole life cycle of compressed air vehicle for the different countries is as the following: Bulgaria—664,060 kWh; average for EU-28 countries—559,850 kWh; Norway—396,540 kWh; Poland—700,400 kWh.

The harmful emissions referred to carbon dioxide for the different countries are as the following: Bulgaria—125,560 kg; average for EU-28 countries—83,860 kg; Norway—3190 kg; Poland—183,950 kg.

The results referred to 1 km run road, are shown in Table 21.

The evaluation of the used primary energy and the carbon emissions throughout the life cycle of the vehicles gives an outlined look for the possibilities of using the energy of compressed air as an alternative method for vehicles driving. The effectiveness of this driving this driving depends only on the Emission factor from the electricity production. For Bulgaria, Poland and EU-28 countries, in terms of assumed emission factors, both CAV give way to GV. For Norway CAV give way

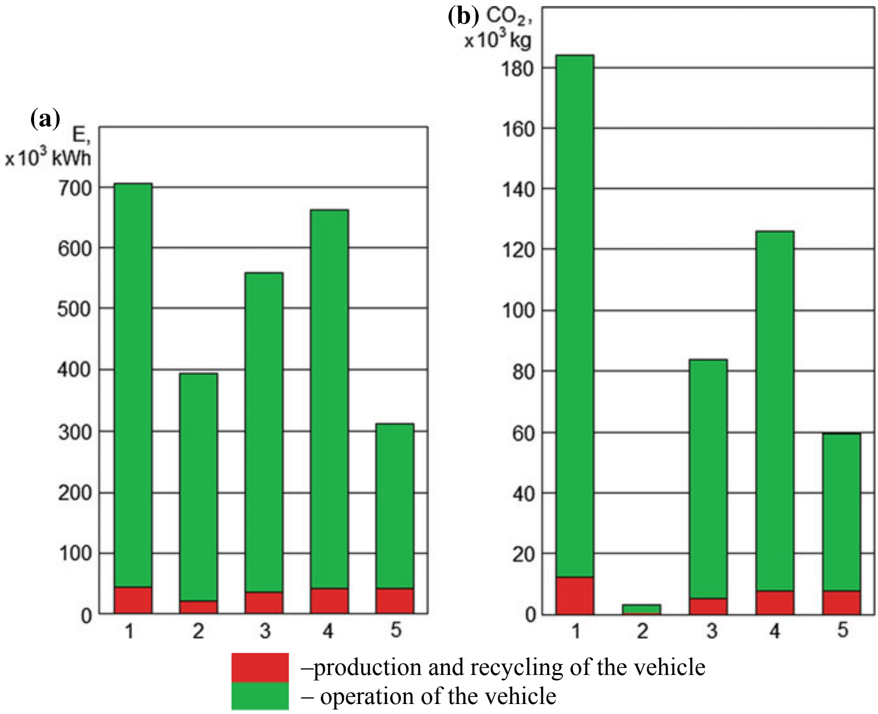


Fig. 48 Life cycle assessment of primary energy (**a**) and CO_2 emissions (**b**) for vehicle, using compressed air and conventional gasoline vehicle [143]: 1—Poland; 2—Norway; 3—average for EU-28 countries; 4—Bulgaria; 5—conventional vehicle produced in Bulgaria

Table 21 Primary energy and CO_2 emissions per 1 km

Vehicle	E, kWh/km	CO_2, g/km
1	2.42	635
2	1.37	11
3	1.93	289
4	2.29	433
5	1.07	206

only in terms of the used primary energy, which is 28% higher, compared to GV but in terms of carbon emissions CAV emit nearly 19 times less through their life cycle.

Economic and ecological parameters of different vehicles impose systematic search of optimal decisions for protecting the environment. The results of evaluation of the life cycle of CAV as ecological vehicles show following. Compressed air has comparatively low energy density app. 50 Wh/l at pressure of 300 bar (~30 MPa) and specific weight 372 g/l. This energy density can be increased substantially if the air is heated before expanding. The main advantage of CAV is the relatively small weight and their ecological production (no batteries) compared to the electric vehicles. At this stage of the development of the technologies, the application of CAV as ecological vehicles independent from the fossil fuels is limited to their use only in urban and suburban areas mainly due to their limited run. Most effective is the use of the energy of the compressed air together with other source of energy—hybrid technologies having better parameters than the ones using energy stored in batteries.

General Conclusion

In this Chapter, energy characteristics of BEV and HEV were presented. Some original experimental results were given. Following this consideration, the Life cycle assessment of main types ecological vehicles was done.

All results are summarized in Table 22 and are shown on Fig. 49. As a base of comparison, the primary energy and CO_2 emissions for conventional gasoline vehicle are used.

The green area (Fig. 49) concerns vehicles, which are more effective in economic and ecological aspects, at average emission factor of EU-28 (see Table 10). For a separate country, this area will be different, depend on the value of its Emission factor of electricity production.

The effect, that electric vehicles do not generate emissions at the place, where it runs, can be used for resolving of local problems with air pollutions, but we have not forgot that its pollutions are generated in power plants, during the electricity production.

The results give a real vision about possibilities to use energy from different types of fuels or electricity, as an alternative, for vehicle propulsion.

At some values of speed and weather conditions, the energy consumption for the supply of auxiliary systems can decrease twice the range of the vehicle. The minimal energy consumption of auxiliary systems is realized at external air temperature of 20°C, at which the biggest range is realized. The light system and signalization consume about 1% of total energy consumption of electric vehicle.

Using RES to produce the electricity is possible to reduce life cycle CO_2 emissions of the BEV up to 40 times than the respective of a gasoline GV.

The use of electricity from HPP can reduce CO_2 emissions from electric vehicles during their life cycle approximately 140 times, compared to the use of electricity produced from fossil fuels (lignite), 65 times compared to the use of electricity from WPP and about 20 times when using electricity from PV plants.

The use of electricity mainly from fossil fuels leads to an increase of global warming problems, due to the generation of more CO_2 emissions from BEV than GV. At an Emission factor of less than 669 g/kWh, according to the accepted conditions in this study, the electric vehicles pollute the environment less than conventional vehicles. The most effective way to decrease the energy consumption and CO_2 emissions for life cycle of the BEV is to change the energy mix by using more energy produced by RES and NPP.

The technology of hydrogen production from natural gas is most effective in countries with CO_2 emissions over 447 g per 1 kWh electricity. The energy spent for life cycle of the FCV, depending on energy mix of the country, can be over 2.5 times

Table 22 Primary energy and harmful emissions of vehicles, powered by the different fuels and energy sources, during their life cycle, per 1 km distance

№	Type of vehicle depending on the power source	Country							
		Bulgaria		EU-28 Member States		Poland		Norway	
		Primary energy, kWh/km	CO_2, g/km	Primary energy, kWh/km	CO_2, g/km	Primary energy, kWh/km	CO_2, g/km	Primary energy, kWh/km	CO_2, g/km
1	GV	1.068	206	1.044	197	1.081	219	1.012	179
2	BEV	1.156	207	1.036	137	1.272	303	0.620	005
3	H_C^EFCV	2.567	506	2.165	338	2.664	741	1.313	013
4	H_L^EFCV	2.833	556	2.389	371	2.940	814	1.449	014
5	H_C^{NG}FCV	1.062	243	1.012	206	1.082	296	0.800	133
6	H_L^{NG}FCV	1.327	294	1.237	239	1.357	370	0.902	134
7	H_C^CFCV	1.893	373	1.806	334	1.914	425	1.621	262
8	H_L^CFCV	2.159	423	2.030	368	2.190	449	1.756	263
9	LPG	0.946	186	0.922	176	0.959	198	0.890	159
10	NG_C	0.985	197	0.948	182	1.005	218	0.893	153
11	NG_L	1.018	219	0.976	197	1.132	250	0.965	154
12	CAV	2.290	443	1.930	289	2.420	635	1.370	011

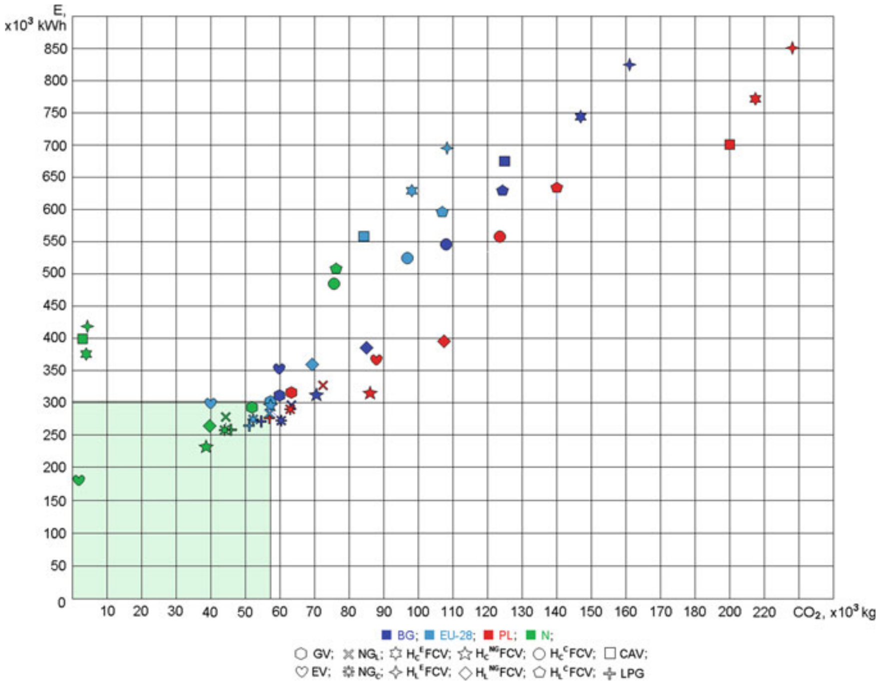


Fig. 49 Primary energy and CO_2 equivalent emissions of vehicles, using different fuels or electricity, during life cycle: BG—Bulgaria; EU-28—average for the EU countries; PL—Poland; N—Norway; GV—conventional gasoline vehicle; EV—Battery electric vehicle; H_C^EFCV—a fuel cell electric vehicle, powered by compressed hydrogen of up to 700 bar, produced by electrolysis; H_L^EFCV—a fuel cell electric vehicle, powered by the liquefied hydrogen, produced by electrolysis; H_C^{NG}FCV—fuel cell electric vehicle, powered by compressed hydrogen up to 700 bar, produced from NG; H_L^{NG}FCV—fuel cell electric vehicle, powered by liquefied hydrogen, produced from NG; H_C^CFCV—fuel cell electric vehicle, powered by compressed hydrogen up to 700 bar, produced from coal; H_L^CFCV—fuel cell electric vehicle, powered by liquid hydrogen, produced from coal; LPG—vehicle, using propane-butane fuel; NG_C—vehicle, using compressed methane; NG_L—vehicle, using liquefied methane; CAV—compressed-air vehicle

higher than the respective for GV. The most ecological technology for production of hydrogen is electrolysis for countries using a large part of renewable energy sources in its energy mix. For example, in Norway FCV will have 16 times less emissions than GV. Positive ecological and financial effects from replacing the vehicle fleet with FCV, now and in near future are not strongly proven.

The production and use of natural gas are in relation to its leakage into the atmosphere, which generates approximately 12% of life-cycle emissions under the accepted test conditions. It emits additionally few emissions from its compression and liquefaction, which in fact diminishes greatly its advantages as an environmental fuel. Vehicles using propane-butane fuel has a less emissions than NG.

Use of the biofuels is an alternative decision, which have not positive ecological effect.

At this stage of the development of the technologies, the application of CAV as ecological vehicles, independent from the fossil fuels, is limited to their use only in urban and suburban areas, mainly due to their limited range.

Most effective is the use of the energy of the compressed air together with other source of energy—hybrid technologies having better parameters than the ones using energy stored in batteries.

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The Impact of Road Transport on the Environment

Jozef Gnap, Branislav Šarkan, Vladimír Konečný and Tomáš Skrúcaný

Abstract Exhaust gas emissions from road vehicles influences the environment and life quality of inhabitants, mainly in urban areas. The production of harmful emissions was rapidly decreased by introducing emission standards and limits. Opposite them, the huge increasing number of operated vehicles, mainly in developed countries f. e. in Europe, it eliminates the advantages of new and environmental friendlier vehicles. One of useful solution for health protection of urban inhabitants seems the introducing and supporting alternative propulsions in vehicles—hybrid vehicles and full electric vehicles. Transport and its direct activities are important consumers of energy and producers of greenhouse gases (GHG). The energy intensity and specific GHG production from transport activities are the key targets of the near future in the course of sustainable transport and mobility. There are different approaches to calculate GHG emissions from transport worldwide. In Europe, this has led to the need to standardize the methodology of GHG emissions calculation, the result is European standard EN 16258.

Keywords Road vehicle emissions · Hybrid vehicle · Energy intensity · GHG production · Sustainability · Transport services

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1 The Impact of Road Transport on the Environment and Reduction Options

Transport is fundamental to our economy and society. Mobility is vital for the internal market and for the quality of life of citizens as they enjoy their freedom to travel. Transport enables economic growth and job creation. It must be sustainable in the light of the new challenges we face. Transport is global, so effective action requires strong international cooperation.

Even despite a significant technical progress, cost-effective energy efficiency improvements and policy efforts the transport system has not fundamentally changed since the 1st big oil crisis 40 years ago. Transport has become more energy efficient, however, 96% of transport energy needs in the European Union still depend on oil and oil products. Transport has become greener, however, due to an increased volume it continues to be the main source of noise and local air pollution [1].

At the beginning of a new millennium one of fundamental characteristics of the society development is still its globalisation which interferes all its areas. Thus, worldwide it also interferes transport. Globalising trends affect an increasing need for transport, whether passenger or freight one. The increase of road passenger and freight transport does not only bring apparent pros but also cons; the biggest negative effect is the impact on the environment. Therefore, there are currently being developed and applied numerous technologies aimed at reducing negative effects of transport and motoring on the environment. The volume of emissions of pollutants in transport is related to the consumption of propellants which negatively impact a technical condition of the operated fleet, capacity utilisation of transport means, and burden of the transport infrastructure. The society imposes pressure on automobile companies, on the development of automobiles with the lowest emissions possible. This trend is strongly supported with the European Union which wants to stimulate automobile manufacturers with new measures to invest into new technologies for the reduction of CO_2 emissions. The tendency and priority of developed and applied technologies depend, however, on the development of the overall economic environment, social sphere, political and legislative factors and technical innovation cycles [2].

In spite of reduced atmosphere pollution from road transport there in urban areas still exist serious problems with the quality of the air. There are other initiatives needed to expose people to pollutants impacting the health to the lowest extent possible. With regard to the environment transport is a source of emissions (whether fundamental pollutants or greenhouse gases), noise and vibrations; it puts a strain on soil, it impacts spatial arrangement and causes health and safety risks. Negative effects of transport on the environment are conditioned with increasing transportation requirements of the society in connection with the process of globalisation which is reflected in demands on the transport infrastructure [3, 4].

The rise of the living standard brings a big growth of road transport volume, particularly the individual one, which requires modernisation and extension of the road network capacity. A quality transport infrastructure is a condition of the economy development and it belongs to basic criteria while making decisions regarding a new investment realisation. More favourable economic conditions for business making, flexibility and ability to respond to requirements of a modern economy have caused that road transport has been achieving a decisive market share, and its increase leads to congestions on main road lines as well as to negative impacts on the environment and health of the population in towns. From the point of view of making the transport green it is important to introduce renewable energy sources within transport, to develop their utilisation, and to put a focus on the support and development of non-motorised and ecological modes of transport [3].

Transport is one of key factors in the development of each modern society, and it itself does not represent a goal but a means of the economic development. The impact of transport on the economy is directly reflected in individual branches of industry producing transport means, in the building industry in the construction of the transport infrastructure, and indirectly in all branches of industry producing raw materials, fuels, semi-finished products, components and machines for transport. Transport negatively impacts the environment from two basic points of view: the construction of the transport infrastructure, and harmful effects from the transport operation. Increasing transport volumes lead to a bigger pressure on the environment, mainly with regard to a change of climate and to a loss of a biodiversity. There exists a positive aspect, too; technological improvements provide a reduction of the air pollution from road transport even despite the growth of transport volumes [3].

1.1 Legislation and Politics in Reducing the Impacts of Transport on the Environment

The impact of transport on the environment in the form of emissions production is closely related to the fuel consumption. It is clear that the smaller the fuel consumption is, the smaller the production of pollutants in exhaust gases is. In the world and European scale there exist several instruments and politics whose role is to eliminate the impact of a man on the environment. Each of these politics may be transformed into international or national legislations later. Individual politics point out the meaning of reducing the emissions production in transport, or road transport.

United Nations Framework Convention on Climate Change (UNFCCC)

It is a multilateral agreement on protection of the Earth's climate system and on limitation of global warming. It represents the first significant international convention dealing with the solution of the climate change. Upon its adoption it was ratified by 196 countries including all EU member states and the EU as an independent subject, too. This convention established a framework for the cooperation of countries to avoid a dangerous anthropogenic interference with the global climate system. In 1997 the convention was added with the Kyoto Protocol. It is an international treaty which establishes legally binding obligations for industrialised countries to reduce their greenhouse gas emissions. In the United Nations Climate Change Conference in 2011 under the impulse of the EU and majority of vulnerable developing countries it was decided to start a new run of negotiations in order to achieve a global treaty on climate which would require all countries, both developed and developing ones, to take action. The new treaty was adopted in Paris in 2015, known as the Paris Agreement. The Paris Agreement on Climate Change is the first general, legally binding global agreement in this area. Contracting parties must present their emission commitments until 2020, and low emission strategies and plans until 2050 [5].

Convention on Long-Range Transboundary Air Pollution (CLRTAP)

This treaty represents a significant instrument to reduce a long-range transmission of air pollutants. It features a framework nature and an own reduction of air pollution is realised on the basis of gradually adopted specific protocols; eight protocols were adopted.

The treaty was approved within the United Nations Economic Commission for Europe on 13 November 1979 in Geneva and currently there are 51 contracting parties [6].

Measures to Protect the EU Climate

The international community agrees that in order to sustain the climate change below a dangerous level the average global temperature must not raise in more than 2 °C, relative to pre-industrial levels. The EU thus strives to:

- reduce emissions of its member states,
- encourage other big polluters to take decisive actions,
- solve unavoidable impacts of the climate change [5].

The EU constantly determines the pace in solving the climate change and supporting a shift to low-carbon economy. The EU efforts in this area began in 1990 when it committed to stabilise its carbon dioxide (CO_2) emissions on the level of that year until 2000, which was fulfilled. Since then the EU has introduced a whole set of political measures to reduce greenhouse gas emissions; many of them were introduced through the European Climate Change Programme launched in 2000. Besides, member states have adopted own national measures. Europe contributes to CO_2 production in approx. 10% (Fig. 1).

The EU representatives set the most ambitious goal values in the area of the climate and energetics for 2020, and the EU is the first region in the world which adopted binding legal regulations to guarantee their observance. In October 2014 the EU leaders strengthened their own commitment in the sense of supporting the competitiveness, safety and sustainability of the EU economy and its energy system through adopting a framework in the area of climate and energetics until 2030. From a long-term point of view the EU set ambitious goals regarding emissions for 2050.

Strategy 2020 The solution of the climate change problem is one of the five main themes of a large Europe 2020 strategy aimed at smart and sustainable growth. Its

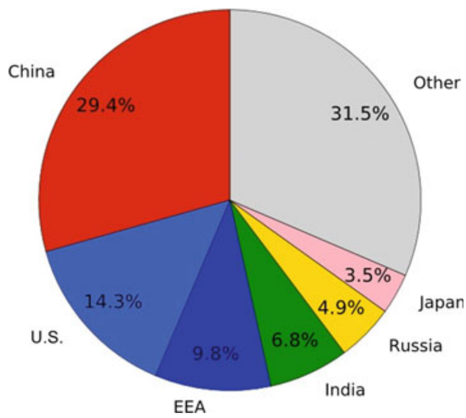

Fig. 1 Structure of CO_2 producers (2017). *Source* Worked out by the author based on [6]

specific targets should ensure that the EU greenhouse gas emissions are cut by 20%, that 20% of energy comes from renewable sources, and that energy efficiency is improved by 20%. The first two targets are accomplished via a climate and energy package on the basis of the binding legislation effective since June 2009. This legislation sets mandatory national target values for renewable energy which reflect different starting points of the member states and a potential to increase the production from renewable energy sources, and it also sets target values for emissions from industries not included in the EU emissions trading system. National targets for renewable energy for 2020 vary from 10% in Malta, where the renewable energy industry is young, to 49% in Sweden, a country with an advanced industry based on bioenergy and water power. These national targets will collectively lead to the achievement of the target value 20% for the EU as a whole which will significantly increase an average share of energy renewables in their energy consumption when compared to 12.5% in 2010.

2030 Framework The integrated politics framework in the area of climate and energetics for the period 2020 to 2030 is needed to ensure regulatory certainty for investors and a coordinated approach among the member states. The framework which was adopted by the EU leaders in October 2014 should stimulate a constant progress in the transformation to a low-carbon economy and it should serve to confirm ambitious goals of the EU during international negotiations on climate. Its goal is to build an energy system that will ensure affordable energy for consumers, increase the security of the EU's energy supplies, reduce our dependence on energy imports, cut greenhouse gas emissions, and create new opportunities for a green growth and job positions. The main element of this legal framework is its binding target to cut greenhouse gas emissions in the EU by at least 40% below 1990 levels by 2030. The efficient reformed system of the EU for the emissions trading represents the main instrument to achieve this target.

Goal until 2050 As its contribution to keep the global temperature increase to well below 2 °C the EU committed (alike developed countries) to achieve a long-term goal to cut its emissions by 80 to 95% when compared to 1990 levels by 2050. To reduce emissions to that extent it will be required for the EU to become a low-carbon economy. In 2011 the Commission published a strategy where it set how to reach a competitive low-carbon economy as effectively as possible by 2050, and it also determined milestones for the progress measurement. This strategy describes how individual industries, from energy production to agriculture, can help to achieve this goal [5].

White Paper—Roadmap to a Single European Transport Area—Towards a Competitive and Resource Efficient Transport System

It is a document by European Commission, 2011, which reports on targets of reducing greenhouse gas production in the transport sector. The analysis shows that while deeper cuts can be achieved in other sectors of the economy, a reduction of at least 60% of greenhouse gas emissions by 2050 with respect to 1990 is required from the transport sector, which is a significant and still growing source of greenhouse gases. By 2030, the goal for transport will be to reduce greenhouse gas emissions to around 20% below their 2008 level. Given the substantial increase in transport emissions over the past two decades, this would still put them 8% above the 1990 level.

From the point of view of developing and deploying new and sustainable fuels and propulsion systems there are for example efforts to halve the use of "conventionally-fuelled" cars in urban transport by 2030, phase them out in cities by 2050, achieve essentially CO_2-free city logistics in major urban centres by 2030 (Fig. 2).

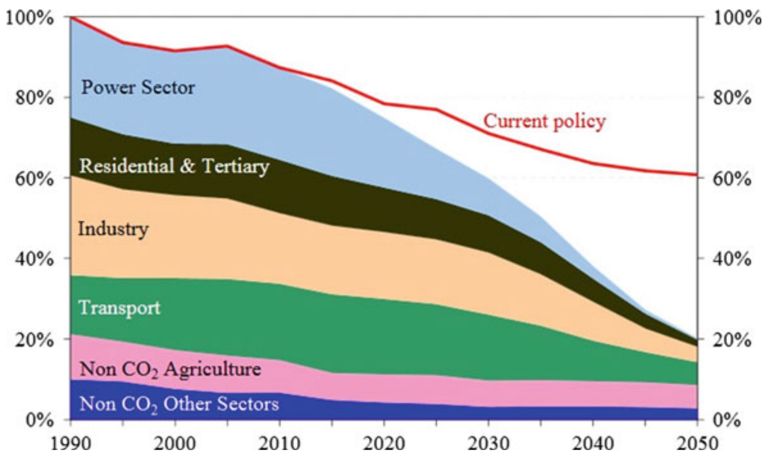

Fig. 2 Development of the EU greenhouse gas emissions towards 80% internal decrease (100% = 1990). *Source* [1]

1.2 Emissions from Road Transport

The atmosphere pollution with emissions significantly contributes to global worldwide environmental problems, such as the climate change. The transport sector belongs to important factors of energy problems and environmental problems as it is one of the biggest consumers of fossil energy sources [3].

Greenhouse Gases

Greenhouse gases are gases causing the greenhouse effect. They include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated greenhouse gases (F-gases) which are divided into groups containing partially fluorinated hydrocarbons (HFC—hydrofluorocarbons), fully fluorinated hydrocarbons (PFC—perfluorocarbons) and sulphur hexafluoride (SF_6). They are emissions emerging from natural processes and human activities, too. The most significant natural greenhouse gas in the atmosphere is water vapour. During the activities of people big volumes of other greenhouse gases are emitted into the atmosphere which increases their atmospheric concentrations. Greenhouse gases are reported in so called CO_2-equivalents; it is a value determining the rate of individual greenhouse gases impact on global warming using a recalculation per the volume or concentration of CO_2, which would have similar impacts. Growing greenhouse gas emissions in the atmosphere strengthen the greenhouse effect which subsequently evokes the change of climate. The transport share on greenhouse gas production for 2012 in the European Union reached 20% (Fig. 3) [7].

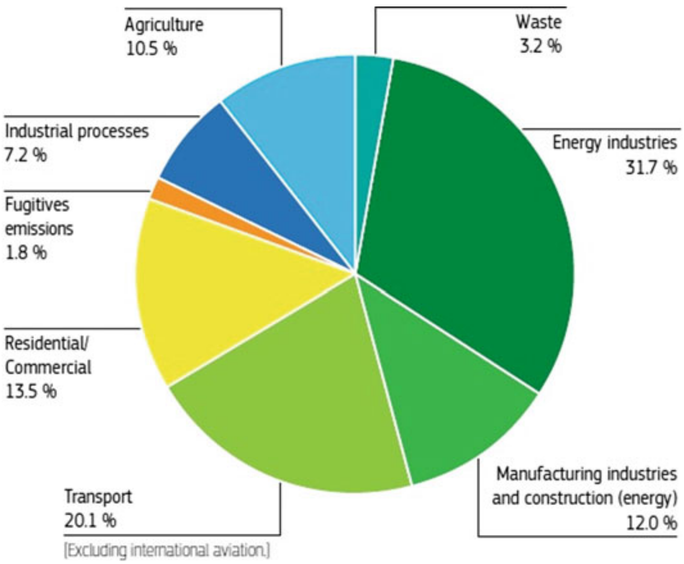

Fig. 3 Share of transport in the greenhouse gas production in the EU, 2012 [5]

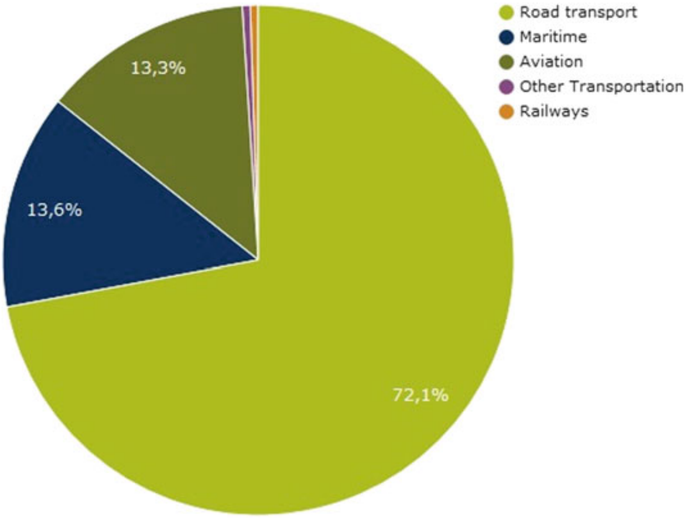

Fig. 4 Share of individual transport types in the greenhouse gas production. *Source* Worked out by the author based on [8]

From the structural point of view of individual transport types impact, the greatest impact on greenhouse gas production is reached by road transport (72.1%), air transport (13.3%) and water transport (13.6%) (Fig. 4).

Basic Pollutants

Basic pollutants include solid pollutants (solid emissions), sulphur dioxide (SO_2), nitrogen oxides (NO_X) and carbon monoxide (CO). Emissions of basic pollutants are classified into emissions emitted from **stationary sources** (generation and distribution of electricity, vapour and hot water, local heating devices, industrial technological processes, fossil fuel production, waste sites and waste processing, agricultural production, and other stationary sources), and **mobile sources** (road transport and other mobile sources).

Solid pollutants are divided into two major groups by their size:

- **PM_{10}** are particles with the diameter from 2.5 to 10 μm, which may easily penetrate into lung tissues and cause health problems in cardiovascular and respiratory system. The source of PM_{10} particles is the cloud of dust from roads, manufacturing plants, combustion of solid substances or exhaust gases from motor vehicles.
- **$PM_{2.5}$** are particles with the diameter less than 2.5 μm and similarly to PM_{10} they have a negative effect on human health, particularly on the airways. Their sources are all kinds of combustion processes including residential combustion of wood, forest fires, power stations, agricultural processes, automobile transport, etc.

Sulphur dioxide is a gas which irritates airways mucous membranes and bulbar conjunctivas; it occurs in exhaust gases of combustion engines; it is produced during the combustion of fossil fuels or during the processing of ores containing sulphur.

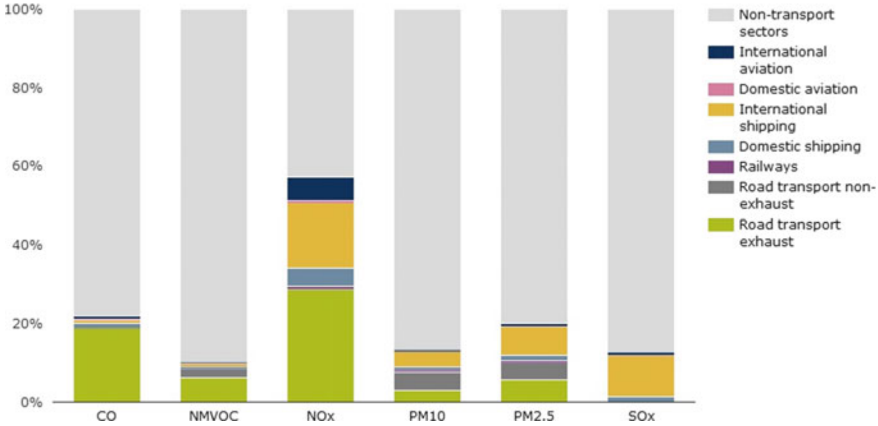

Fig. 5 Share of individual transport types in the basic pollutants production [9]

Nitrogen oxides originate in technical facilities where high temperature combustion occurs, and they are also part of exhaust gases. They may cause moderate to severe bronchitis or pneumonia, and they also contribute to the damage of the Earth's ozone layer, to the acidification of rainfalls, and smog formation.

Carbon monoxide is a product of combustion from industrial furnaces, boilers and other technological devices combusting gas, liquid and solid fuels, and it is the most harmful constituent of exhaust gases. The main negative effect of CO lies in blocking the supply of oxygen to tissues. Typical symptoms of poisoning with CO include headaches and dizziness, heart problems and lassitude.

Non-methane volatile organic compounds (NMVOC) include all organic anthropogenic compounds other than methane which in reaction with nitrogen oxides produce photochemical oxidants with ozone as their most significant member. Ozone is an especially toxic substance which negatively impacts human health and vegetation even in very small concentrations. Main sources of volatile organic compound emissions include: using of paints and adhesives, dry cleaning and degreasing, oil processing, and transport [7].

Figure 5 shows shares of individual transport types in the production of basic pollutants. Road transport is a significant producer of carbon monoxide (approx. 20%) and nitrogen oxides (approx. 30%).

1.3 Emissions of Road Vehicles

Approval Process of Road Vehicles from the Point of View of Emission Production

The operation of a combustion engine is based on combustion of a fuel and air mixture on the basis of the oxidation of fuel combustible constituents with oxygen, which occurs in the air and fuel in a combustion chamber with rapidly changing temperatures and pressures. During the combustion there occur mutual reactions of individual constituents under high temperatures and pressures with a heat and pressure energy release. These reactions lead to the formation of constituents in all states emitting from the combustion chamber, and some constituents react and emerge only during their passage through an exhaust pipe. The progress of combustion is affected with heat, form and swirl properties of the combustion chamber, and mainly with the method and quality of fuel injection. According to actual analyses the exhaust gases of internal combustion engines contain almost 160 different constituents, but only 0.3% represents harmful emissions in exhaust gases.

Besides products of perfect combustions, i.e. CO_2, H_2O, excess of oxygen, and residual nitrogen which are of a dominant occurrence, there is a plenty of gases and solid substances with the highest focus put on carbon monoxide—CO, unburned hydrocarbons—HC (paraffins, olefins, aromates), partially burned hydrocarbons (aldehydes, ketones), fission products (acetylene, ethylene, hydrogen, carbon particles), nitrogen oxides—NO_X (nitric oxide, nitrous oxide, nitrogen dioxide) and solid particles [10].

Currently there in a vehicle design a big importance is particularly assigned to its ecological operation, and/or to the reduction of its ecological burden on the environment. Thus, each newly manufactured vehicle in the European Union must adhere to an applicable emission standard. These are so called approval (homologation) tests intended to ensure that each vehicle in the market produces a maximum limit value of individual harmful substances in exhaust gases.

The European standard for automobile engines is created by the Economic Commission for Europe (ECE) within the Agreement Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts. These ECE's regulations are applicable in most of European states. There within the European Union operates the Motor Vehicle Emission Group (MVEG), which is part of the EU administration, and which represents the most competent body for the standard base pertaining to the emission assessment of automobiles.

During its operation a road vehicle must undergo a regular emission control in an emission control station. With respect to the methodology, demandingness as well as required technical equipment we speak about diametrically opposed test types [11].

Emission Limits of Passenger and Light-Duty Vehicles

One of possible ways how to achieve a lower production of emissions from road vehicles operation is to set emission limits for vehicle manufacturers. The volume of emissions which may occur in automobile exhaust gases is set in emission standards which are gradually made stricter. The first regulation applicable to passenger vehicles in Europe was the ECE's Directive No. 15 introduced in 1971. In its original version it contained 4 driving cycles and considered a measurement of carbon monoxide (CO) and unburned hydrocarbons (HC). Later a measurement of nitrogen oxides (NO_X) was added. The test was modified and amended over the years. After many adaptations the ECE's Directive No. 15 was replaced with a new regulation No. 83 of the ECE in the late 80 s. It has become a keystone for regulations applicable even nowadays.

The entire process of these tests takes place under laboratory conditions when a vehicle undergoes a driving testing in a performance test room during a prescribed driving cycle (vehicle speed in time). During the entire cycle respective harmful pollutants are collected and evaluated in g/km units. The entire driving cycle which consists of four ECE-15 cycles and one extra-urban driving cycle (EUDC) is called NEDC (New European Driving Cycle). In 2017 it was replaced with a cycle labelled as WLTC (Worldwide Light-Duty Test Cycle).

Table 1 summarises the development of emission limits for passenger vehicles with a spark-ignition engine. All emission values are given as a mass number, i.e. in grams per kilometre. The given values make it clear that the higher the Euro emission standard is, the stricter the assessment of individual emission values is.

Table 2 states limit values for vehicles with a compression ignition engine which show multiple toughening of individual values over years.

The ECE's Regulation 83 has been amended several times since 1989; these modifications were mostly related to toughening of limit values. At the beginning of the 90 s there in individual legislations of the European Union states new emission regulations emerged; they were based on the ECE's Regulation 83, and their name is derived from the EU convention. These emission regulations are better known under

Table 1 Development of emission limits for passenger vehicles with a spark-ignition engine

	Month and year of launch	CO	HC	HC + NO_X	NO_X	PM
		[g/km]				
Euro 1	7/1992	2.72		0.97		
Euro 2	1/1996	2.2		0.5		
Euro 3	1/2000	2.3	0.2		0.15	
Euro 4	1/2005	1	0.1		0.08	
Euro 5	9/2009	1	0.1		0.06	0.005
Euro 6	9/2014	1	0.1		0.06	0.005

Table 2 Development of emission limits for passenger vehicles with a compression ignition engine

	Month and	CO	HC	HC + NO_X	NO_X	PM
	Year of Launch	[g/km]				
Euro 1	7/1992	2.72		0.97		0.14
Euro 2	1/1996	1		0.9		0.1
Euro 3	1/2000	0.64		0.56	0.5	0.05
Euro 4	1/2005	0.5		0.3	0.25	0.025
Euro 5	9/2009	0.5		0.23	0.18	0.005
Euro 6	9/2014	0.5		0.17	0.08	0.005

the name of EURO (sometimes only the acronym EU is used) followed with a number of the regulation revision. Within the unification of legislation these regulations have been adopted in other states outside of the European Union, too. Their label is the same as the respective version of the ECE's Regulation 83 (e.g. ECE 83.03).

Regulations defining individual emission standards:

- EURO 1 (EU 1): In 1992 the Regulation 91/441/EC, known as EURO 1, came into force in the states of the European Union.
- EURO 2 (EU 2): Since 1 January 1996 Regulations 94/12/EC and 96/69/EC, labelled as EURO 2, have been effective in the European Union states. These standards brought stricter limits again and they came into force in states conforming to the ECE regulations in 1996.
- EURO 3 (EU 3): Since 1 January 2000 the Regulation 98/69/EC—A (EURO 3) has been effective in the states of the European Union. This regulation considers a separate assessment of nitrogen oxides (NO_X) and unburned hydrocarbons (HC) emissions, which were assessed together before. Moreover, changes were partially related to the arrangement of the driving cycle.
- EURO 4 (EU 4): It was amended with regulations 98/69/EC and 2003/76/EC, and it has been valid since 2005.
- EURO 5, 6 (EU 5, EU 6): Euro 5 (October 2009) and Euro 6 (2014) for passenger and light-duty vehicles—2007/715/EC. Thanks to the introduction of conditions of Euro 6c/d the regulation above has been amended with the Regulation 2017/1151/EC, which introduces the usage of Global Technical Regulation No. 15 (the Worldwide Harmonized Light Vehicles Test Procedures—WLTP). Part of the Regulation 1151/2017/EC is a requirement to test emissions in standard running. The test is called RDE (Real Driving Emissions) [11].

Emission Limits for Lorries

European emission classes for new heavy-duty vehicles with compression ignition engines are commonly referred to as Euro I to Euro VI; sometimes Arabic numerals are also used. Emission standards apply to all motor vehicles with a "technically permissible maximum laden mass" over 3,500 kg, equipped with compression ignition engines or spark-ignition engines, combusting natural gas (NG) or LPG.

Standards were originally introduced with Directive 88/77/EEC, followed by a number of amendments. The following are some of the most important steps.

Euro I standard was introduced in 1992. In 1996 it was replaced with Euro II standard. These emission requirements were applied to lorry engines. They were also applied to urban buses; however, they were only voluntary for them.

In 1999, the EU adopted Directive 1999/96/EC, which introduced Euro III standards (2000), as well as Euro IV/V standards (2005/2008). This directive set stricter emission limits for extra low emission vehicles, known as "enhanced environmentally friendly vehicles" or EEVs.

Table 3 Development of emission limits for lorries

Stage	Date	Test	CO [g/kWh]	HC [g/kWh]	NO_X [g/kWh]	PM [g/kWh]	Smoke [m^{-1}]
Euro I	1992 < 85 kW	ECE R-49	4.5	1.1	8.0	0.612	
	1992 > 85 kW		4.5	1.1	8.0	0.36	
Euro II	1996/October		4.0	1.1	7.0	0.25	
	1998/October		4.0	1.1	7.0	0.15	
Euro III	1999/October, EEVs	ESC and ELR	1.5	0.25	2.0	0.02	0.15
	2000/October		2.1	0.66	5.0	0.10 0.13	0.8
Euro IV	2005/October		1.5	0.46	3.5	0.02	0.5
Euro V	2008/October		1.5	0.46	2.0	0.02	0.5
Euro VI	2013/January		1.5	0.13	0.4	0.01	

Directive 2005/55/EC was adopted by the European Parliament in 2005. It introduced durability and on-board diagnostic (OBD) requirements, and it also re-stated emission limits for Euro IV and Euro V which were originally published in 1999/96/EC.

Euro VI emission standards were introduced with the Regulation 595/2009, published on 18 July 2009 (followed by a number of amendments as of 31 July 2009). The new emission limits have been effective since 2013 (new approvals) and 2014 (all registrations) [12] (Table 3).

Road vehicles are subject to various forms of measures in their operation. There wear away parts which may be responsible for the produced volume of harmful substances in exhaust gases. Therefore, it is a social requirement to control road vehicles for their production of harmful pollutants during their operation regularly.

However, in common operation it is difficult to perform a repeated test of approval regulations. It is because these tests are conducted and evaluated by means of highly expensive devices which should be part of equipment of all facilities controlling these values. In common operation during the emission control it is necessary to perform the test quickly and with the lowest possible costs. Road vehicles are thus controlled in emission control stations where volume compositions of prescribed exhaust gases constituents are controlled using simple analysers [12].

1.4 Emissions in the Operation of Road Vehicles

A motor vehicle emission control means a control of the vehicle engine's condition and its system which impact the production of pollutants in exhaust gases, and the manufacturer's adherence to the set conditions and emission limits of the engine, found out with a measurement. The emission control is performed in a stationary emission control station or a mobile emission control station per the control operations set for individual emission controls [11].

The emission control serves to control a motor vehicle:

- with a spark-ignition engine with a not advanced emission system,
- with a spark-ignition engine with an advanced emission system,
- with a spark-ignition engine with an advanced emission system equipped with an on-board diagnostic system (OBD),
- with a compression ignition engine,
- with a compression ignition engine equipped with an on-board diagnostic system (OBD),
- with a compression ignition engine re-designed to a spark-ignition gas fuel-powered engine,
- with a spark-ignition engine re-designed to an alternative gasoline-powered engine.

Emission Control Evaluation

As it has already been described in the introduction of this chapter prior to its launch into the market a vehicle must meet a regulation regarding the production of pollutants in exhaust gases, effective for the given period. During the operation a road vehicle is then controlled in a form of a test during an emission control which is performed in prescribed intervals. Depending on the kind of engine power (a vehicle with a spark-ignition or compression ignition engine, or a compressed natural gas or petroleum gas engine) and the year of its manufacture its emission limits are defined either by the manufacturer or legislation (if the manufacturer has not determined the limits).

Emission Limits of Motor Vehicles in the Operation

Volume concentration of carbon monoxide and unburned hydrocarbons in idle engine speed of an unburden spark-ignition engine with a not advanced emission system cannot exceed emission limits set by the manufacturer. If the manufacturer has not determined the limits, the set emission limits are as follows:

- maximum 6.0% of carbon monoxide and 2000 ppm of unburned hydrocarbons for a vehicle with a spark-ignition engine, which was registered before 31 December 1972 for the first time,
- maximum 4.5% of carbon monoxide and 1200 ppm of unburned hydrocarbons for a vehicle with a spark-ignition engine, which was registered before 31 December 1985 for the first time,
- maximum 3.5% of carbon monoxide and 800 ppm of unburned hydrocarbons for a vehicle with a spark-ignition engine, which was registered after 1 January 1986 for the first time (Table 4).

The volume concentration of carbon monoxide, unburned hydrocarbons and the Lambda value with the engine speed of an unburden spark-ignition engine with an advanced emission system cannot exceed limits set by the vehicle's manufacturer. If the manufacturer has not determined the limits, the set emission limits are as follows:

Table 4 Emission limits of vehicles with a spark-ignition engine with a not advanced emission system

Date of the first registration	CO [%]	HC [ppm]
Before 31.12.1972	6	2.000
From 1.1.1973 to 31.12.1985	4.5	1.200
After 1.1.1986	3.5	800

Note The volume capacity of HC is given in ppm (parts per million) units and the following is true:
100% vol. = 1,000,000 ppm, 1% vol. = 10,000 ppm

Table 5 Emission limits of vehicles with a spark-ignition engine with an advanced emission system

Date of the first registration	Idle speed		Higher revolutions	
	CO [%]	HC [ppm]	CO [%]	λ
Before 30.6.2002	0.5	100	0.3	0.97–1.03
After 1.7.2002	0.3		0.2	

- the highest concentration of carbon monoxide with idle engine speed cannot exceed 0.5% of carbon monoxide, and for vehicles registered after 1 July 2002 for the first time it cannot exceed 0.3%; the highest concentration of unburned hydrocarbons cannot exceed 100 ppm,
- the highest concentration of carbon monoxide with a higher engine speed in the range from 2,500 min^{-1} to 3,000 min^{-1} cannot exceed 0.3%, and for vehicles registered after 1 July 2002 for the first time it cannot exceed 0.2%; the Lambda value cannot exceed values set by the vehicle's manufacturer or it must be in the range 1 ± 0.03 (Table 5).

Emissions of visible pollutants of exhaust gases (smoke emission) of a compression ignition diesel fuel-powered or dual diesel fuel and natural gas/liquefied petroleum gas-powered engine, found out with a method of free acceleration, cannot exceed emission limits set by the vehicle's manufacturer. If the manufacturer has not determined the limits, the set emission limits are as follows:

- maximum 4.0 m^{-1} for a vehicle with a compression ignition engine, which was registered before 31 December 1979 for the first time,
- maximum 3.0 m^{-1} for a vehicle with a forced-induction compression ignition engine, which was registered after 1 January 1980 for the first time,
- maximum 2.5 m^{-1} for a vehicle with a not pressure charged compression ignition engine, which was registered after 1 January 1980 for the first time,
- maximum 1.5 m^{-1} for a vehicle with a compression ignition engine, which was registered after 1 July 2008 for the first time,
- maximum 0.7 m^{-1} for a vehicle with a compression ignition engine, which was registered after 1 January 2015 for the first time (Table 6).

During the emission control the condition of the vehicle or the function and operations of individual systems impacting the production of pollutants in exhaust gases of the vehicle are evaluated with a two-stage classification.

Table 6 Emission limits of vehicles with a compression ignition engine

Date of the first registration	Smoke emission [m^{-1}]
Before 31.12.1979	4
After 1.1.1980—a forced-induction engine	3
After 1.1.1980—a not pressure charged engine	2.5
After 1.7.2008	1.5
After 1.1.2015	0.7

Based on the result of the evaluation of the vehicle's condition and function of individual systems a motor vehicle is:

- capable of driving on land communications,
- incapable of driving on land communications.

Development of CO and HC Values on the Basis of the Vehicle's Age and Emission System Kind

When evaluating the development of CO and HC emission values we use data from the emission control operation in the Department of Road and Urban Transport at the University of Žilina in Žilina from 2005 to 2014. During this period there were 8,780 motor vehicles with a spark-ignition engine, M1 category, driven for the test, with the following numbers of individual emission systems:

- 6,954 vehicles—a not advanced emission system without a device for an additional reduction of pollutants in emissions from the exhaust pipe,
- 126 vehicles—a not advanced emission system with a device for an additional reduction of pollutants in emissions from the exhaust pipe when the preparation of the mixture is not controlled depending on the concentration of free oxygen in exhaust gases,
- 1,700 vehicles—an advanced emission system of a motor vehicle with a device for an additional reduction of pollutants in emissions from the exhaust pipe when the preparation of the mixture is controlled depending on the concentration of free oxygen in exhaust gases.

The information above implies that the biggest number of vehicles undergoing the emission control was represented with vehicles without a catalytic converter. Figures 6, 7 and 8 show a visible drop of the controlled volume concentration of CO (%) in case of the emission system with a controlled catalytic converter below 1%. It is obvious that current vehicles with controlled operations of the entire engine produce significantly less emissions than vehicles with emission systems without a controlled catalytic converter.

Figures 9, 10 and 11 allow monitoring the development of average values of HC depending on the year of the vehicle's manufacture for individual emission systems. While older vehicles without a catalytic converter achieved HC values from 200 to

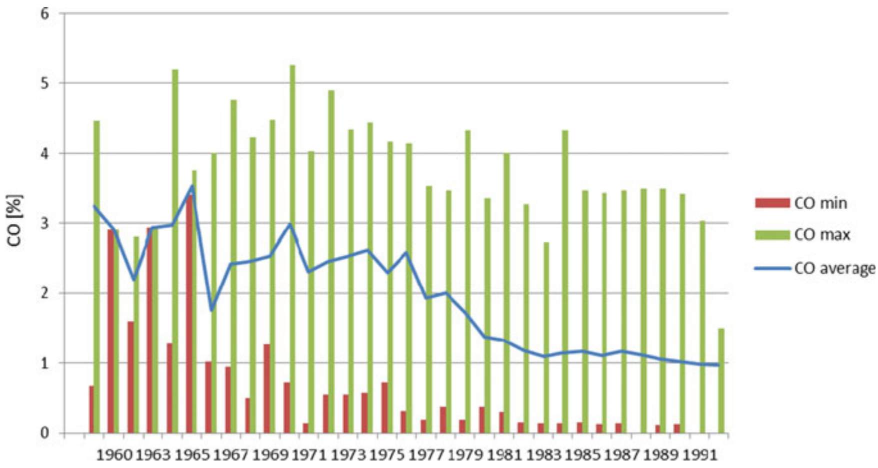

Fig. 6 CO [%] for vehicles without a catalytic converter

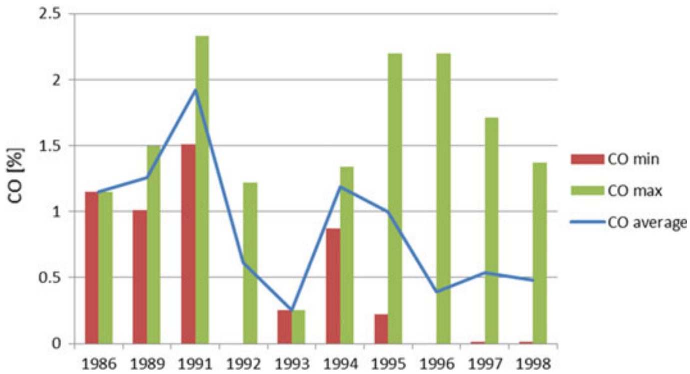

Fig. 7 CO [%] for vehicles with an uncontrolled catalytic converter

1000 ppm depending on the year of the vehicle's manufacture, current vehicles which are equipped with controlled catalytic converters feature HC values around 10 ppm when measured in idle engine speed.

1.5 Measurement of Emissions in the Operation of Road Vehicles—Case Studies

Case Study No. 1—Measurement of a Vehicle's Emissions in Urban Operation

The case study deals with a method for calculating the exhaust emissions of a passenger vehicle during its drive in an urban area. For this calculation a running test was

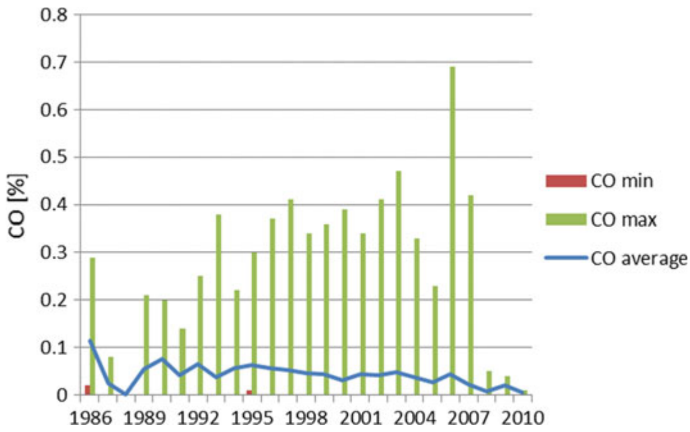

Fig. 8 CO [%] for vehicles with a controlled catalytic converter

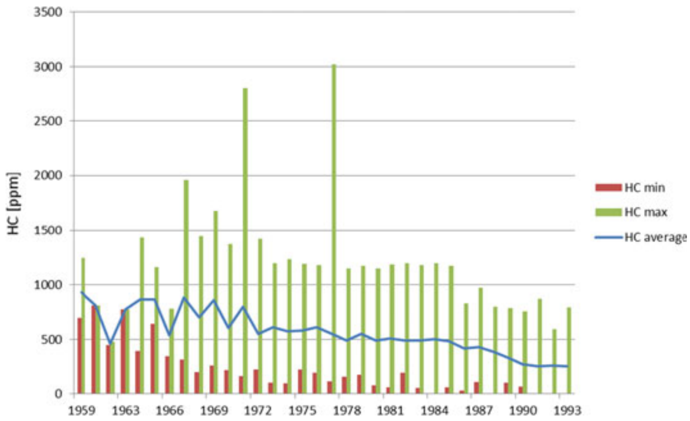

Fig. 9 HC [ppm] for vehicles without a catalytic converter

conducted in which exhaust gas volume data and engine control data was recorded. The exhaust gas constituents evaluated are nitrogen oxide, hydrocarbon, carbon monoxide, and carbon dioxide. The data recorded from the engine control unit is the engine speed, intake air quantity, vehicle speed, and intake air temperature. The exhaust constituents are calculated in gram per kilometre of a vehicle drive.

The Department of Road and Urban Transport has a measurement technique available which makes it possible to use known calculation procedures to determine a volume of produced emissions of exhaust gases during a vehicle's drive in grams per kilometre. A basic measuring device is an exhaust gas analyser Maha MGT 5. This gas analyser is capable of measuring HC, CO, CO_2, O_2 and NO_X emissions. The principle of the analyser's work lies in a selective absorption when each constituent is evaluated in the area of infrared radiation. Tested exhaust gases are carried from an

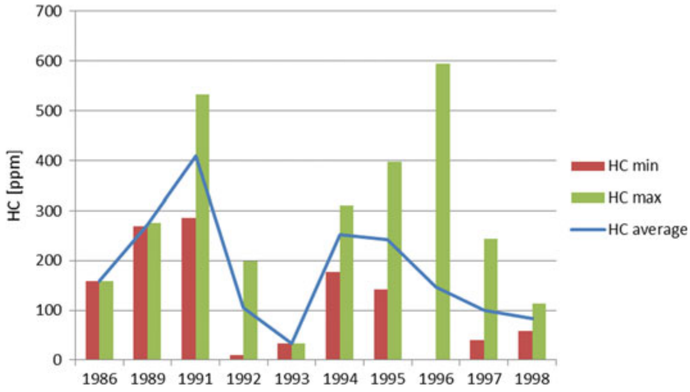

Fig. 10 HC [ppm] for vehicles with an uncontrolled catalytic converter

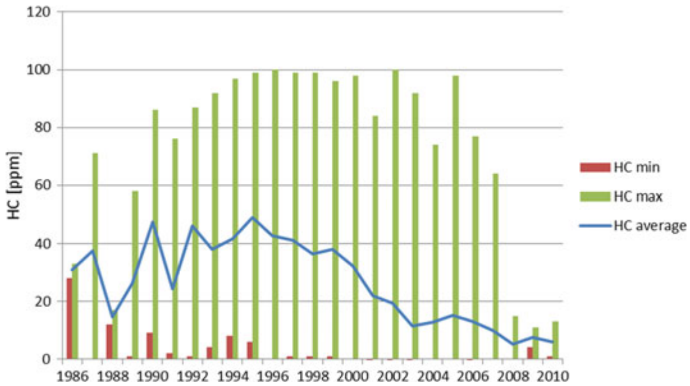

Fig. 11 HC [ppm] for vehicles with a controlled catalytic converter

exhaust pipe of a vehicle using an exhaust probe which is connected to the analyser with a pipe. First of all, water vapour H_2O is separated from the exhaust gases which are then carried to a measuring chamber. An infrared light beam in the direction of a measuring element is weakened with the gas; depending on the kind of the gas the weakened condition of the light beam is manifested with a various wave length. This way the volume of HC, CO, CO_2 is measured. On the other hand, O_2 and NO_X are measured using an electrochemical detection. The data measured by the emission analyser is evaluated on a laptop with Maha Emission Viewer software which enables to record emissions throughout the drive of the vehicle (Fig. 12).

In order to record data from the engine control unit a simple Bluetooth OBD ELM327 device paired with a mobile phone was used. The mobile phone processed and stored the data using the Torque Pro application. The following data was stored: volume of the aspirated air MAF (g/s), speed of the vehicle (km/h), revolutions RPM, and temperature of the aspirated air IAT (°C). The application also allows for

Fig. 12 Scheme of data acquisition and processing

recording the GPS positions of the vehicle which can be used to evaluate the data regarding its route. All measured and stored data is transferred into an evaluation computer where known methods are used to evaluate the vehicle's emissions in g/km [13]. The data from the emission analyser is 8 s delayed with regard to the transfer of emissions from the exhaust pipe to the analyser [14]. The frequency of data recording is 1 Hz.

The emissions during a drive of the vehicle were measured in Toyota RAV 4, year of manufacture: 2015. The vehicle is driven with a spark-ignition engine with the engine capacity of 1,987 cm^3, with a maximum power of 112 kW and with a torque of 195 Nm. The vehicle is subject to the EURO 6 emission standard with the following emission values: CO = 0.384 g/km, NO_X = 0.012 g/km, HC = 0.032 g/km, CO_2 = 159 g/km.

The vehicle was operated in an urban ring in Žilina while performing the measurement. The route was 9.3 km long and the measurement was repeated 3-times (Fig. 13).

The measured exhaust emission values in a volume expression had to be converted into a mass expression. For this purpose, the methodology published by the following author was used: *Kuranc A.: Exhaust Emission Test Performance with the Use of the Signal from an Air Flow Meter* [15].

The cumulative values of the individual emission constituents are processed by this methodology for all three measurements. The course of individual constituents of the emissions while driving the vehicle is shown in Fig. 14.

The parameters of each driving were affected by the traffic situation. During three measurements there were achieved maximum speeds of 66, 70 and 69 km/h, and average vehicle speeds of 36.11, 33.96 and 37.89 km/h. The whole speed course of the vehicle during the measurement No. 1 is shown in Fig. 15.

In Table 7, the exhaust gas constituents are calculated for all three measurements in grams per kilometre, and these values are compared to the vehicle type approval

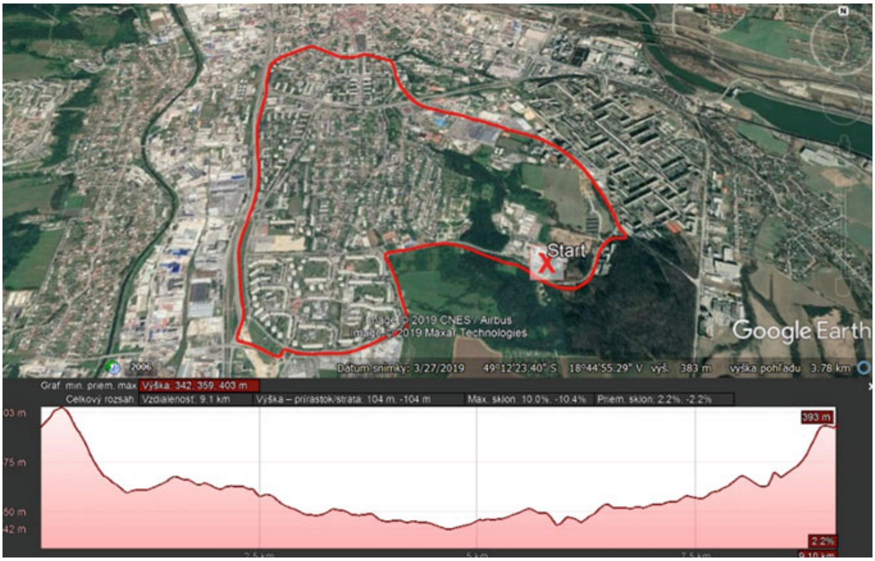

Fig. 13 Route of the urban ring in Žilina

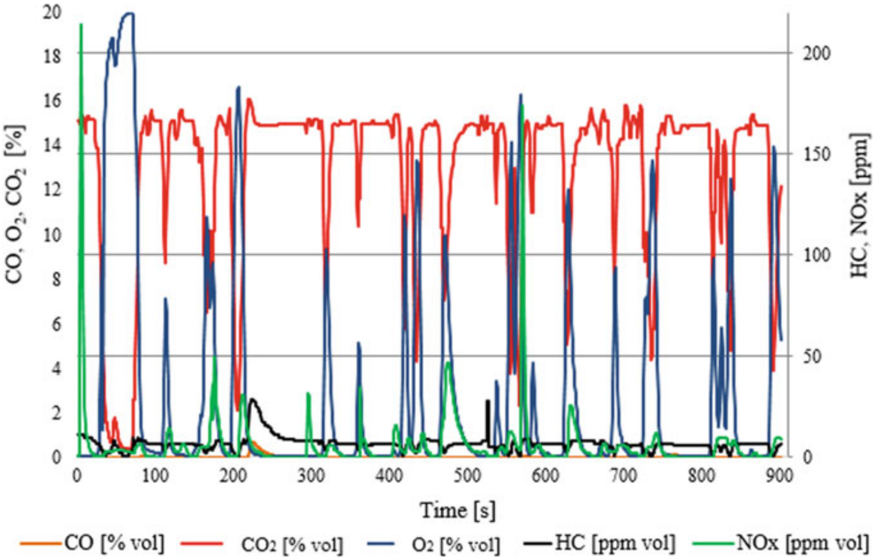

Fig. 14 Course of individual emission constituents while driving the vehicle

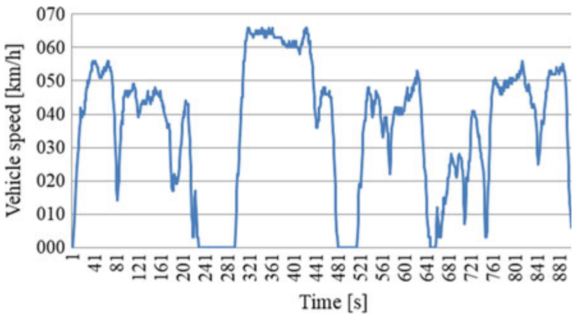

Fig. 15 Course of the vehicle's speed during the measurement No. 1

Table 7 The comparison components of emissions' values

Emissions components	Values from the measurements			Type approval values
	No. 1	No. 2	No. 3	
CO_2 [g/km]	169.26	156.40	170.35	159.00
O_2 [g/km]	0.0164	0.012	0.0150	–
CO [g/km]	0.165	0.1253	0.1039	0.384
HC [g/km]	0.0167	0.0178	0.0240	0.032
NO_X [g/km]	0.0066	0.0073	0.0101	0.012
Average speed [km/h]	36.11	33.96	37.89	

values. As we can see, especially the HC values are significantly different from those measured on a dynamometer in a laboratory.

The next part of the results is aimed at comparing the different driving modes of the vehicle within the first emission measurement. The measurement No. 1 took 902 s in total and this time period was divided into four different driving modes. Then the exhaust gas constituents were calculated for each driving mode separately. Four modes were selected: the standing of the vehicle (idle mode), the steady drive mode, the acceleration mode and finally the vehicle deceleration mode.

Up to 13% of the total measurement time the vehicle was in the idle mode, which was mainly due to the traffic situation on a given measurement route. This was also due to the presence of light-signalling devices on the measurement route. During the first measurement, the vehicle was stopped three times with a total duration of 114 s (Table 8). For almost half of the total measurement time the vehicle was moving at a steady speed (steady drive), and for the rest of the time the vehicle was accelerated and decelerated. To compare the constituents of the exhaust gas, the individual constituents had to be calculated in grams (not in grams per kilometre). This is in order to make it possible to compare the production of emissions while the vehicle is stationary (in the idle mode).

In order to be able to compare the driving modes with each other, not only the total emissions production was quantified in the driving modes, but also the individual

Table 8 Emission values during different vehicle driving modes during the measurement No. 1

Emissions components	Idle	Steady drive	Acceleration	Deceleration
Whole drive 902 s	114 s	396 s	210 s	182 s
CO_2 [g]	69.491	671.27	704.115	129.278
O_2 [g]	0.957	68.25	13.303	70.083
CO [g]	0.1505	0.3401	0.8993	0.1471
HC [g]	0.0087	0.0612	0.0722	0.0139
NO_X [g]	0.00199	0.00998	0.03402	0.01601

constituents of emissions were recalculated per one second. These values are shown for each constituent of emissions in Figs. 16, 17, 18 and 19.

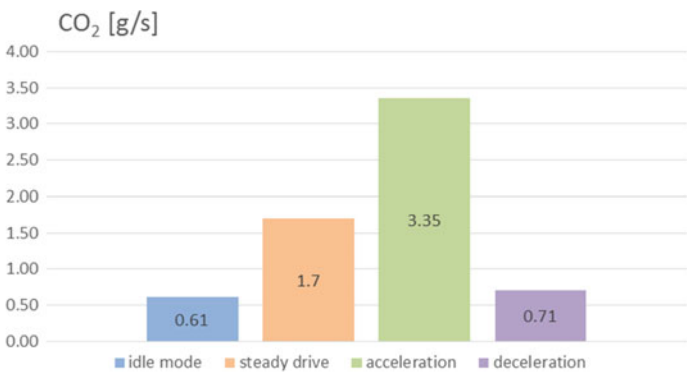

Fig. 16 The amount of CO_2 (g/s)

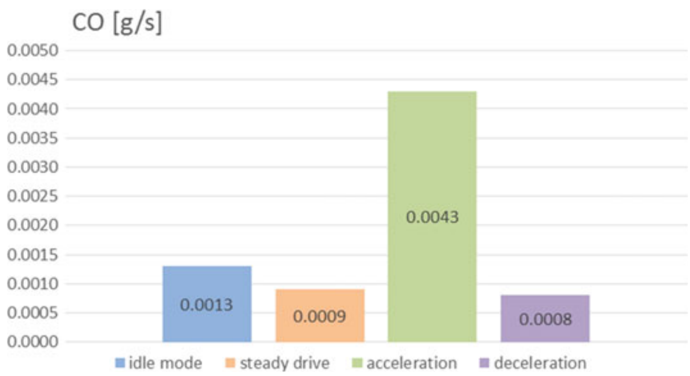

Fig. 17 The amount of CO (g/s)

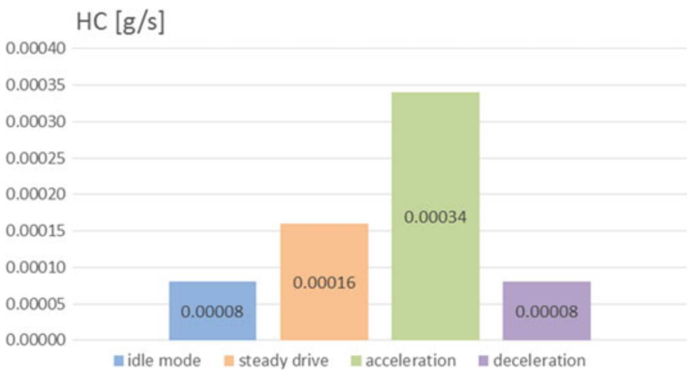

Fig. 18 The amount of HC (g/s)

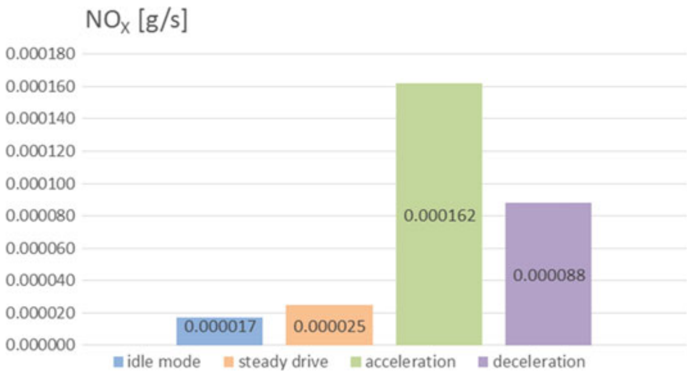

Fig. 19 The amount of NO_X (g/s)

The method of measuring the emissions of passenger cars during their urban and extra-urban operation is nowadays an obligation in the vehicle type-approval process. The method of calculating the emissions using a simple exhaust gas analyser is an alternative to the PEMS method, especially in scientific researches. It allows a relatively fast and cheap measurement method. Results from this kind of measurement can be used to determine the impact of road transport on selected areas of cities (Table 9).

Table 9 Measurements results

Drive	Duration [s]	Electro duration [s]	Average speed [km/h]	Maximum speed [km/h]	Measured distance [km]	Electric engine duration [s]
1	1.329	894	27.4	57.8	10.153	900
2	1.620	1.220	22.4	61.4	10.122	1.221

The results show that the way the vehicle is driven has a significant impact on the amount of produced emissions. If a vehicle in one area of the city has to accelerate constantly, this will affect the amount of emissions produced in that area. For the purpose of quantifying the impact of road transport on the environment it is necessary to have the most accurate data on the traffic flow structure available. There are differences in emissions in case of lorries and in case of passenger cars. However, differences can be observed in vehicles with a petrol engine and diesel engine, too.

Data from such types of emission measurements should in future serve, for example, for making decisions in cities where to introduce emission zones and where to prohibit the entry of vehicles of a particular category or emission system.

Case Study No. 2—The Importance of Hybrid Vehicles in Urban Traffic in Terms of the Environmental Impact

Many large cities in Europe are currently trying to reduce the amount of harmful substances for their residents. Road transport is also an important source of air pollution. One way to reduce the pollutant production is to operate more environmentally friendly vehicles. The paper analyses data obtained during practical tests of a hybrid vehicle in urban traffic. The individual constituents of the exhaust gases are calculated in g/km and they are compared to the values for conventional vehicle propulsion. The data was obtained through a commercially available exhaust gas analyser, and a calculated amount of emissions produced was got from available data from the engine control unit. The results showed that the usage of this type of propulsion has its importance in cities with increased air pollution. During the urban operation the hybrid-powered vehicle was powered by an electric engine up to 67.70% (75.40% of the time). As a result of operating such a vehicle in the city emissions of CO_2, HC and NO_X were significantly lower.

The number of road vehicles in operation significantly affects the amount of emissions produced and thus the fuel consumption in the transport sector [16]. There in the transport sector, especially in road transport, an increase in the number of road vehicles can still be observed. The number of registered vehicles in Europe is constantly growing at a rate of around 2% year-on-year. The negative environmental impact of road traffic is mitigated by the introduction of new technologies in power trains, but their increasing number eliminates this advantage [17, 18].

The composition of vehicles in service is a significant factor that affects the environmental impact of road transport. The composition of road vehicles can be looked at in terms of the mode of transport (passenger cars, lorries, buses and others), the type of propulsion (petrol engine, diesel engine, alternative type of propulsion) or their age structure. The driving performance of individual types of road vehicles is also an important factor [19, 20].

All these factors represent the basic input for calculating the environmental burden of road vehicles. Passenger cars account for almost 87% of all vehicles in operation. The EU motor vehicle fleet is getting older year-on-year. On average passenger cars are 11.1 years old, vans are 11 years old and heavy-duty vehicles are 12 years old (year 2017). In 2018, diesel's share of the market fell from 44.0 to 35.9%, while petrol continued to further expand its share within new car registrations (from 50.3 to 56.7%). The market share of hybrid-electric vehicles in the EU was 2.7% of all new car sales in 2017. In 2017, plug-in hybrid (PHEV) and battery-electric vehicles (BEV) made up about 1.4% of vehicle registrations in the EU. This is a slight increase when compared to the previous year. [20] In the area of reducing the negative environmental impacts caused by humans, a significant increase in the number of vehicles with alternative propulsion types would be expected.

In order to assess the impact of a hybrid vehicle in the urban traffic, two measurements were made in Žilina during the traffic peak hours of the day. The route led from the campus of the University of Žilina to the city centre, and back. The route had approximately 10 km (Fig. 20). While driving, the exhaust gas parameters were recorded and selected data from the engine control unit was recorded via OBD diagnostics.

Exhaust emissions measurement in a real vehicle operation was performed on TOYOTA RAV4 vehicle with a hybrid drive and gearbox CVT—Continuously Variable Transmission. This vehicle features four-wheel drive. It is powered by a petrol engine VVT-i (2AR) with the engine capacity of 2,494 cm^3 with a maximum power of 114 kW and a torque of 206 Nm. This hybrid vehicle has two electric engines. The front electric engine has a power output of 105 kW and a torque of 270 Nm, and the rear high-speed electric engine has a power output of 50 kW and a torque of 139 Nm, which provide electric drive for both axles. The total combined power of the hybrid system is 145 kW. The vehicle has the following emission values (EURO 6) with

Fig. 20 Driving route of a hybrid vehicle

an average fuel consumption of 5.1 l/100 km: CO 0.2670 g/km, NO_X 0.0090 g/km, CO_2 118 g/km, HC 0.0490 g/km.

The hybrid vehicle TOYOTA RAV4 was moving at the average speed of approximately 27.4 km/h in measurement No. 1, and in the measurement No. 2 the average speed of the vehicle was even lower, namely 22.4 km/h. The total time duration of the first emission measurement was 1,329 s, of which up to 900 s (which is 67.70%) of the time the petrol engine was switched off and the propulsion was provided by two electric engines. The total time duration of the second measurement on the test route was 1,620 s, out of which up to 1,221 s (which is 75.40%) of the time the petrol engine was switched off. When the petrol combustion engine is switched off, there is no emission of exhaust gases [21–23]. There in measurements such a situation happened most often while driving at low speed, driving at steady speed, decelerating the vehicle, and while the vehicle was standing at intersections, and so on. The petrol engine was switched on again upon a request to achieve higher vehicle acceleration.

Using the recorded data from the engine control unit (vehicle speed and engine speed) and using the emission values it is possible to analyse in which operating states the electric engine and petrol engine were during the operation. The course of vehicle speed and engine speed is shown in Fig. 21 for measurement No. 1.

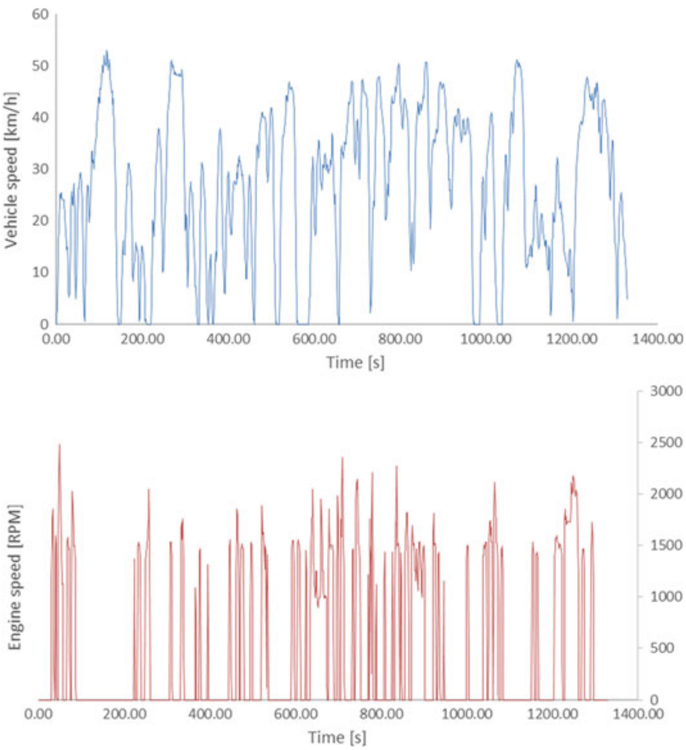

Fig. 21 Vehicle and engine speed

In urban traffic, the duration of vehicle's zero speed was 102 s for the measurement No. 1, and 208 s for the measurement No. 2. Figure 22 shows the distribution of the operation of the electric engine and the petrol engine as a function of the vehicle speed. The vehicle speed was divided into intervals of 10 km/h with a separate speed separation for speed 0 km/h (the part when the vehicle was stationary). In this case, the vehicle produced no exhaust emissions [24, 25]. At speeds of up to 30 km/h, especially during the acceleration phases, the vehicle was predominantly powered by the electric engine.

Exhaust emissions were recorded by a Maha MGT 5 emission analyser with Maha Emission Viewer software. Emission values in g/km were calculated using the already published methodology using data from the engine control unit. The basic parameter needed for the calculation is the amount of intake air. The amount of intake air was measured by an air quantity sensor in the intake manifold and expressed in g/s. In Table 10, the resulting calculated amounts of CO_2CO_2, O_2, CO, HC and NO_X emissions are expressed in grams per kilometre of drive.

In previous publications the author published the results of emissions measurements during the operation of the Toyota RAV 4 vehicle on the same urban route

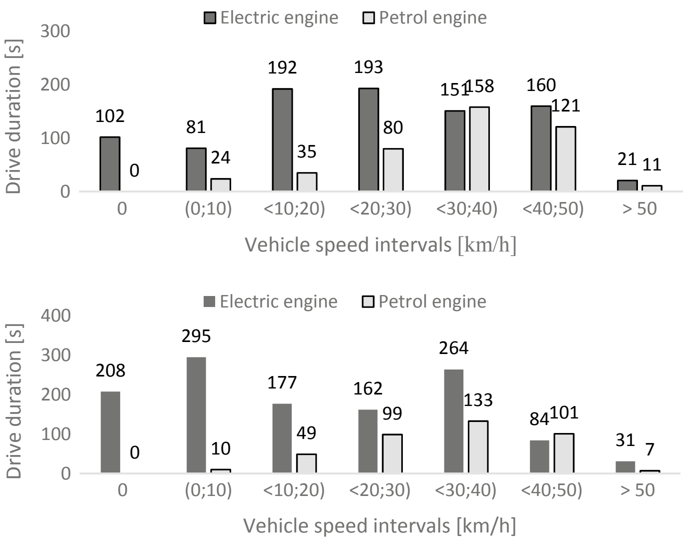

Fig. 22 Vehicle and engine speed

Table 10 Emissions Results of Toyota RAV 4 Hybrid

Drive	CO_2 [g/km]	O_2 [g/km]	CO [g/km]	HC [g/km]	NO_X [g/km]
No. 1	136.354	0.027	0.301	0.134	0.00015
No. 2	123.214	0.025	0.156	0.015	0.00001

Table 11 Emissions Results of Toyota RAV 4

Drive	CO_2 [g/km]	O_2 [g/km]	CO [g/km]	HC [g/km]	NO_X [g/km]
No. 1	169.2647	0.0164	0.1653	0.0168	0.0067
No. 2	156.4008	0.0128	0.1253	0.0178	0.0074
No. 3	170.3572	0.0151	0.1039	0.0240	0.0101

with the following results (Table 11). When compared to the operation of a hybrid vehicle, the production of CO_2, HC and NO_X pollutants is significantly lower.

Emission standards are increasingly stricter and the limit values for the individual exhaust constituents of road vehicles are also stricter. For this reason, emissions are becoming the most watched element of road vehicles. This is mainly because harmful constituents, such as carbon dioxide CO_2 and nitrogen oxides NO_X are part of greenhouse gases and they participate in the global warming, which is currently considered to be the most serious global environmental problem. That is why the European Union continues striving for cleaner transport by imposing strict emission limits for road vehicles. If the emission limits are not respected, car manufacturers will be charged a fee of € 95 for each gram of carbon dioxide produced per kilometre of CO_2 above the set limit of 95 g/km. Other restrictions include the exclusion of older vehicles (which meet lower emission standards) from urban centres for a better air quality in cities.

In order to categorise vehicles according to the individual emission standards they meet, it is important to know the emissions and constituents of the exhaust gases they produce, and especially, to what extent. Therefore, road vehicles must be approved for the emissions production before being placed on the market. At present, emissions are measured under laboratory conditions, where the emissions of a vehicle placed on a roller dynamometer are measured by simulating the driving cycle WLTP. Such measurement results are emission values in grams per kilometre. It is understandable that laboratory emission values measured this way may differ from the emissions actually produced in real operation. Since 2017 laboratory measurements have also been complemented with measurements performed during the actual driving of a vehicle in traffic, called RDE—Real Driving Emissions. The purpose is to get more accurate emission determination.

Case Study No. 3—Proposal for a Procedure for Assessing the Benefits of Using a Hybrid Car Technology for the Environment in Smaller Cities

Exhaust emissions from road transport represent a significant source of air pollution. Reducing greenhouse gas emissions from road transport is one of the European Union's key priorities. For example, the objectives set out in the White Paper—Roadmap to a Single European Transport Area, as mentioned in the introduction, are adapted to this priority. Passenger cars are responsible for about 44% of the emissions generated by transport and represent an important element for reducing greenhouse gas emissions. The EU has also set a specific regulation for manufacturers to reduce CO_2. The aim was to produce vehicles whose drive units produce on average less than 130 g CO_2/km. This goal was already met by 2015, and a new threshold of 95 g CO_2/km has been set to be met by 2021. However, greenhouse gases do not comprise only carbon dioxide, although it is the largest constituent. CO_2 is a pollutant especially for the environment—it creates a greenhouse effect and thus contributes to global warming. Nitrogen oxides, sulphur oxides, carbon monoxide and solid particles—$PM_{2.5}$ and PM_{10}—are much more dangerous with regard to public health [26].

PM_{10}—the concentration of solid particles in the air was exceeded only for 24-h averaging periods at 12 automatic monitoring stations; this value was not exceeded for the annual averaging period. The concentration for the 24-h period is 50 $\mu g\ m^{-3}$ and the maximum number of exceedances per year is 35 days. The number of exceedances at individual stations was from 36 to 82 days (see Table 12), while the highest value was recorded at the monitoring station in the town of Jelšava. However, this is a specific place with a high concentration of solid fuel heating, location of magnesite factory and characteristic geomorphological and weather conditions. For other stations, mostly of a transport type, it is possible to record a greater number of exceedances of PM_{10} concentrations than the statutory limit is. The concentration of solid particles in the air as well as the number of days of exceedance there in Slovakia is influenced by weather conditions and frequent occurrence of inverse weather days, especially in autumn and winter, and also by geomorphological characteristics of the surface. This causes problems especially in the mountainous parts of Slovakia, including the city of Žilina. Žilina is situated in the middle of Žilina Basin and is characterised with a frequent occurrence of days with inverse weather [27].

$PM_{2.5}$—for $PM_{2.5}$ particles, only an annual concentration with the limit of 25 $\mu g\ m^{-3}$ is set. In 2017 it was exceeded at two monitoring stations—Jelšava, Jesenského, and Žilina, Obežná. In case of the measuring station in Jelšava the assumed

Table 12 Measured values of air pollutants at a monitoring station in Slovakia in 2017 [27]

Monitoring station	Measured value of NO_2[$\mu g\ m^{-3}$]	Number of days with PM10 over 50 $\mu g\ m^{-3}$	Measured value of CO [$\mu g\ m^{-3}$]
Bratislava—Trnavské Mýto	39	24	–
Košice—Štefániková	31	55	2,148
Banská Bystrica—Štefánik. nábrežie	38	67	2,238
Nitra—Štúrova	35	27	1,466
Prešov—Arm. gen. L. Svobodu	38	51	2,214
Trenčín—Hasičská	31	41	3,686
Trnava—Kollárová	37	29	1,584
Žilina—Obežná	25	44	2,156

reason for the exceedance is the same as for PM_{10} particles; in case of the station in Žilina, which is close to the first class road I/18, there is a more significant share of road transport with a considerable influence on the concentration of solid particles in the air [27].

Žilina, the regional capital, lies in a basin and at the same time it is a very important road junction of both Slovak and international importance which impacts the quality of air. In 2017 and 2018 the Faculty of Civil Engineering of University of Žilina in Žilina was conducting an additional monitoring of the air pollution in various places in Žilina so the reliability of a mathematical model for a dispersion study could be evaluated. The biggest concentrations of solid particles were recorded during the measurement of a monitoring station in Komenského street. The average daily concentration of PM_{10} for the entire measurement was 86.5 $\mu g/m^3$, for $PM_{2.5}$ it was 66.8 $\mu g/m^3$, and for PM_1 it was 62.1 $\mu g/m^3$. Higher concentrations of solid particles were results of the combination of a significant source—road transport with low temperatures (the average temperature was −2.2 °C) and inversion. The resultant average daily concentrations of solid particles for the measurement performed in the pedestrian zone on the square Námestie A. Hlinku were as follows: $PM_{10\text{-}2}$7.2 $\mu g/m^3$, $PM_{2,5}$—23.9 $\mu g/m^3$, and $PM_{1\text{-}2}$2.8 $\mu g/m^3$. During the measurement a low air temperature (the average temperature −6.3 °C), but a higher wind speed (1.7 m s^{-1}) were also recorded. These measurements served as verification and calibration measurements for long-term continual measurements.

There in Komenského street long-term measurements were in progress; they showed that the traffic burden in urban radials is really high and it causes the excess of emission limits when combined with unfavourable climatic conditions.

The concentration of CO_2 in the air has experienced historical highs in recent years; 405.5 ppm (2017) which was 5.5 ppm higher than in 2015. Moreover, the concentration does not have a decreasing character, but it increases every year. The EU has been trying to stop this upward trend, and cars can also contribute to it. Because of the combustion, those cars with combustion engines produce CO_2 (Fig. 23). Its amount depends on a number of factors—engine emission class, fuel used, vehicle age, driving style, fuel consumption, etc. In case of cars with a conventional combustion engine, this level is approximately from 100 to 200 g CO_2/km. However, this number is much more favourable if we look at new passenger cars sold within the EU and Norway. In these cars the amount of CO_2 produced ranges from 134 g/km in Estonia to 93 g/km in Norway. This is where we can see a decline in sales of hybrid or electric vehicles that produce significantly less or no carbon dioxide.

Transport as a whole there in the Slovak Republic contributes to the produced CO_2 emissions by approximately 16 percent (road transport has the largest share), while a slightly increasing trend can be seen. However, this upward trend is very small when compared to the trend of an increase in the number of cars, the total number of transportations in road freight transport, etc. It is therefore clear that if measures to reduce CO_2 emissions from transport were not taken, the trend of increasing carbon dioxide emissions would be much greater, given the growing number of cars [26, 28, 29].

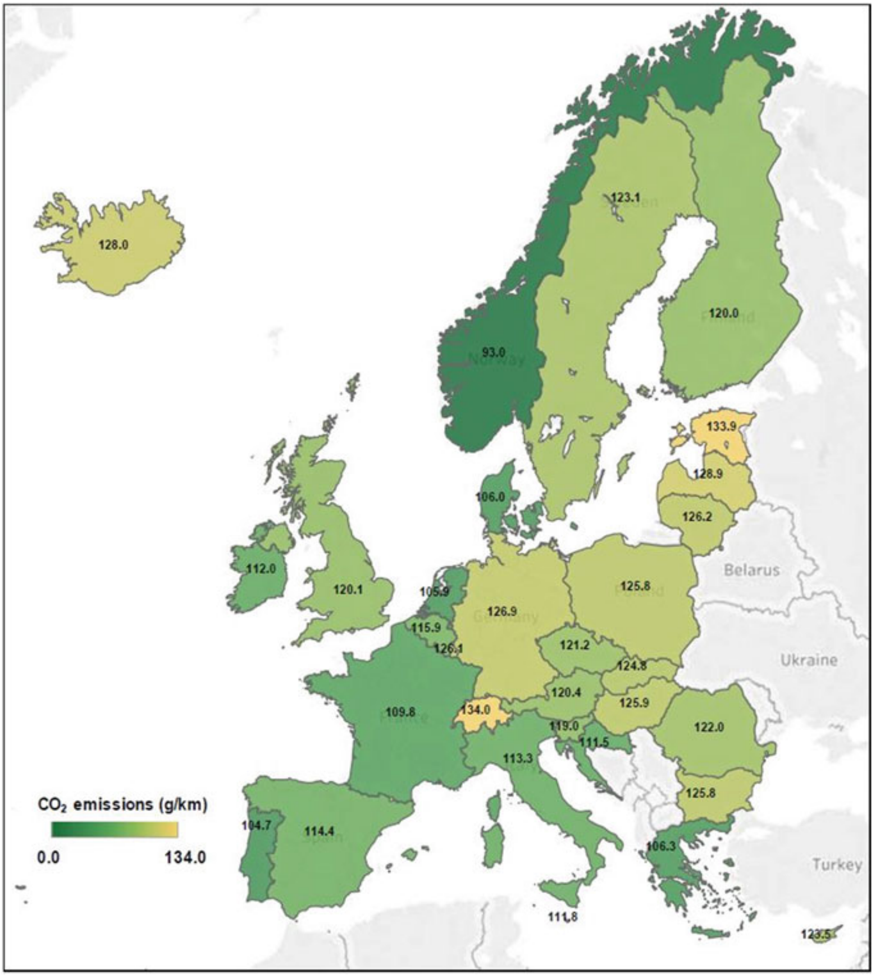

Fig. 23 Average CO_2 emissions from new passenger cars for the EU-28 + Norway, Iceland and Switzerland in 2016 [26]

Measurement Methodology

For the experimental measurement of the emission production in the urban environment Toyota RAV 4, fourth generation of hybrid vehicle technology (2016), was used. In terms of objectives and scientific questions the driving urban circuit road was set in Žilina. The circuit included a significant number of crossings through various types of intersections (uncontrolled intersections, small roundabouts, large roundabouts, light-controlled intersections). The circuit also contained several short ascents and descents in order to ensure field diversity. The terrain diversity is particularly important because of the increase in vehicle resistance when moving up, what caused increased demands on the performance of the hybrid vehicle propulsion technology. The total length of the circuit was 9.98 km. Two measurements were performed on the circuit in the morning.

Part of the city circuit was also a passage through the section equipped with an automatic traffic counter. Traffic data from the automatic traffic counter was evaluated from the measurement date and used to calculate emission reductions. During the entire measurement period the values from the vehicle engine control unit and the log of the exhaust emission data was recorded. Data recording from the engine control unit was made using an OBD interface. The MAHA MGT-5 emission tester was used to analyse and record exhaust gas data.

In addition to measuring the emissions on the urban circuit, emissions measurements and the ratio of using the combustion engine in an underground garage were observed, too. Underground garages and parking houses are a necessity nowadays and they are often part of shopping centres where many people occur. Although the parking spaces are ventilated, their visitors are exposed to a direct inhalation of exhaust pollutants. As vehicles move at very low speeds in parking garages, we expect hybrid cars will be operated in an electrical mode. The aim was to quantify the level of a purely electric drive (non-emission drive) for a hybrid vehicle in an automatic mode (without a manual preference of a fully electric mode).

Measurement Results

A number of operational characteristics of the vehicle and, in particular, the composition of the exhaust emissions were recorded during driving on the circuit. Both measurements were performed with normal vehicle on-board equipment, such as heating, radio, on-board system, and other, switched on. The following data was evaluated from the measured data:

- the type of energy for the vehicle operation,
- the presence of exhaust emissions in the exhaust pipe,
- driving and stopping time of the vehicle,
- type of energy used to drive,
- type of energy used during the stop time [13].

The first drive on the circuit lasted 22 min and 9 s, reaching an average speed of 27 km/h. The vehicle was driving for less than 94% of the time. Electricity was used for 64% while driving. The engine was never switched on while the vehicle was stopped. During one third of the whole operation, the vehicle used a combustion engine to drive. However, emissions were present in the exhaust pipe for a longer time than the combustion engine was in operation. Therefore, this parameter was also evaluated. Emissions from the operation of the internal combustion engine were present in the exhaust pipe for 11 min and 33 s (Fig. 24).

The second drive on the circuit lasted longer, exactly 27 min. The average speed in the second measurement was 22 km/h. Similarly, the proportion of the standing time was higher than in the first measurement, namely at 11%. However, the use of the electric engine increased to 72% while driving; overall, it was 75% of the time of

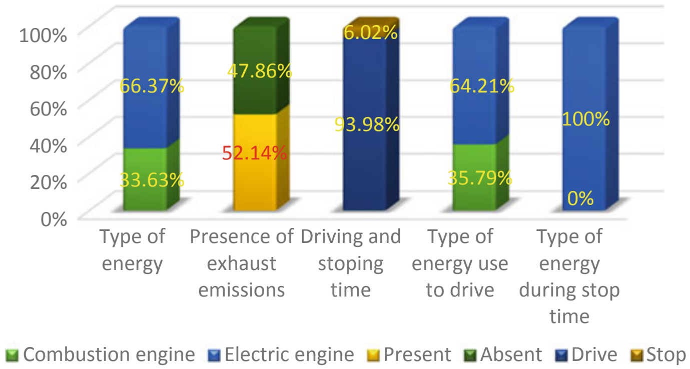

Fig. 24 A relative expression of operating characteristics during the first drive

operation. Emissions from the combustion engine were present in the exhaust pipe for 37% of the operating time, that is, 10 min and 3 s (Fig. 25).

The third measurement took place in an underground parking garage of a shopping centre (Fig. 26). The drive duration was 6 min and 6 s. The results from the drive confirmed the assumption that hybrid car technology would prefer being powered by electric power at low speeds. The measurement results showed that up to 94% of the total time (05:45) it was the electric energy which was used for the vehicle's drive. The combustion engine was used to drive for only 21 s in total. Emissions from the operation of the combustion engine were only present in the exhaust pipe for 31 s. It should also be noted that the start-up of the combustion engine was related only to the drive on steeper ramps between the floors of the parking lot. The vehicle also allows the electric mode (EV mode) to be switched on manually, in which case the combustion engine would not be started [30].

Calculation of Benefits

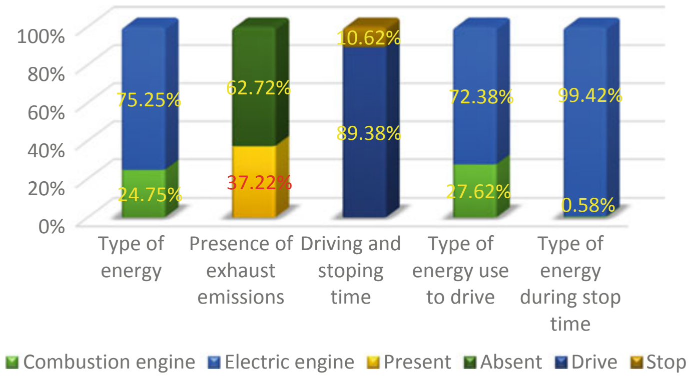

Fig. 25 A relative expression of operating characteristics during the second drive

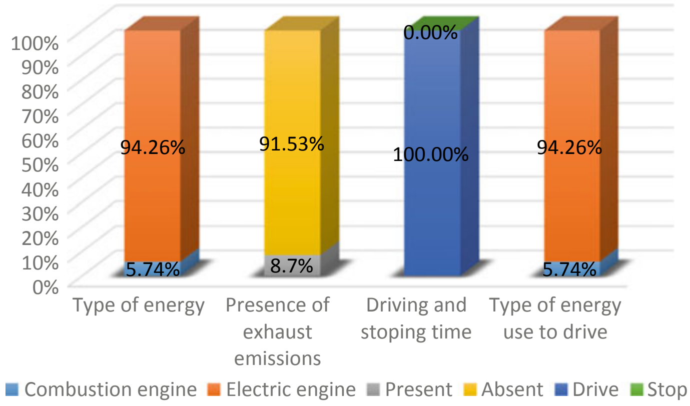

Fig. 26 A relative expression of operating characteristics during driving in an underground garage

The calculation of saved emissions was based on the data obtained from the automatic vehicle counter. Also, the specific production of CO_2 emissions from measurements made by a hybrid vehicle was quantified. The calculation of the specific production of CO_2 emissions during the measurement was carried out by the employees of the Department of Road and Urban Transport of the University of Žilina. The CO_2 emission parameter has been chosen as a benchmark because CO_2 reduction is one of the main objectives of the strategy papers, such as the Paris Agreement, the White Paper on transport, etc. The CO_2 production level is also the main parameter mentioned in the vehicle technical specification.

In the first measurement, the CO_2 production was 136 g/km. For the second measurement, the CO_2 production was 123 g/km. An average rounded value of 130 g CO_2/km was chosen for further calculation.

For the calculation, the savings in CO_2 emissions were selected in the calendar week in which the measurement took place—the 43rd calendar week 2018. Only passenger cars are included in the calculation (Table 13).

Table 13 The traffic intensity in the 43rd calendar week 2018 from an automatic traffic counter

Date	Direction A (number of passenger cars)	Direction B (number of passenger cars)	Together (direction A and direction B)
22.10.2018	12,974	10,713	23,687
23.10.2018	12,445	9,825	22,270
24.10.2018	12,669	10,752	23,421
25.10.2018	12,912	10,218	23,130
26.10.2018	12,644	10,463	23,107
27.10.2018	7,541	5,891	13,432
28.10.2018	6,408	4,785	11,193
Together 48/2018	77,593	62,647	140,240

The following factors are crucial for the further calculation of emission savings:

- length of the transport route,
- the composition of the traffic flow in terms of emission levels,
- saturation of the traffic flow with vehicles featuring the hybrid drive technology [13].

We have chosen 10 km for the length of the transport route, which corresponds to the length of the test circuit. We have modelled emissions savings for various transport streams in terms of emissions. The calculation is made for a car fleet with average CO_2 emissions of 190, 170 and 150 g/km. It should be noted that several current vehicles have an average CO_2 production level of over 190 g/km. The calculation is modelled to saturate the traffic flow with vehicles with the hybrid drive technology for 5, 10, 15 and 25%.

The view of reducing the CO_2 production in a relative expression at individual levels of saturation of the traffic flow by hybrid vehicles may not seem striking. However, expressing the savings in CO_2 production in absolute terms provides a different view. Even at 5% saturation of the traffic flow through hybrid vehicles, weekly savings can reach more than 4 t of CO_2 (Fig. 27). Depending on the car fleet, weekly CO_2 savings can be as high as 7–21 t in case of one fourth of saturation of the traffic flow by hybrid cars (Fig. 28).

By comparing the two measurements of the operating characteristics and the drive of the Toyota RAV 4, hybrid car of the fourth generation, it can clearly be concluded that the efficiency of the hybrid technology is growing with increasing traffic problems. In the second drive, a lower average speed, and a higher proportion of stopping time in traffic was achieved. However, a higher share of electric drive was achieved when compared to the first drive (75%:66%). But the most important aspect is the achievement of 13 g/km lower CO_2 production than in the first drive. These results clearly show the efficiency of the hybrid drive in urban traffic. At

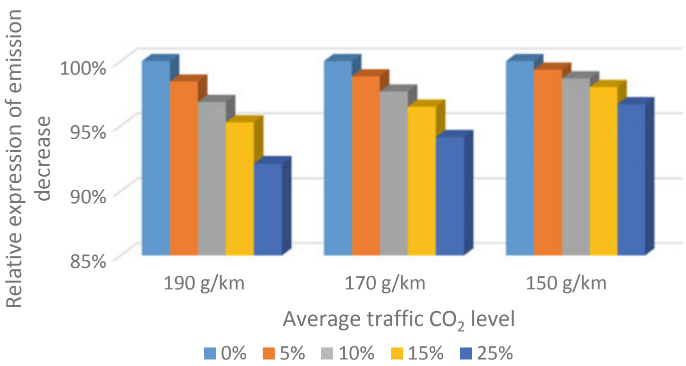

Fig. 27 Decrease in the direct emission production by deploying hybrid cars in saturations levels of a traffic flow in a relative expression. *Source* [13]

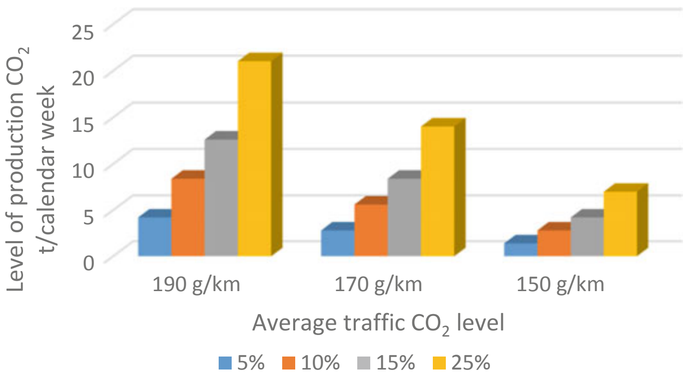

Fig. 28 Savings in the production of direct emissions by deploying hybrid cars in saturations levels of a traffic flow. Calendar week values in an absolute expression. *Source* [13]

present, there are also significant congestions in smaller towns, especially in rush hours. Many smaller towns also face the lack of a bypass infrastructure.

This fact causes transport in smaller towns to be often realised in close proximity to or directly through residential areas and town centres with a high concentration of residents who are subsequently exposed to negative externalities from traffic. These externalities include direct inhalation of exhaust emissions. Measurements in the underground garage showed that the use of a hybrid vehicle at low speeds means the operation is almost without the need for a combustion engine. There in residential areas and urban zones with an adjusted maximum speed, vehicles drive at lower speeds. In these zones results of measurements from the underground garage can be used by analogy. The use of hybrid vehicles in these zones can have a significant positive effect on the air quality of these micro areas.

Especially in countries and cities where there is a high proportion of older vehicles and vehicles with higher levels of emissions production, the promotion of alternative-propulsion vehicles should be supported. In case of some saturation of the transport flow by hybrid vehicles there is a rapid decline in CO_2 emissions. This is also the case for lower levels of saturation of the traffic flow by vehicles with an alternative type of drive. This means that sales promotion measures can produce significant results in a very short time. The measures in question should mainly be acceded by the countries of Central and Eastern Europe, where there is an increased import of used vehicles which do not comply with the new, strict, regulatory measures in Western European cities.

It should also be noted that an even more significant reduction in CO_2 emissions can be achieved with hybrid vehicles primarily designed for urban traffic (e.g. Toyota Yaris) [31].

2 Energy Intensity of Road Transport

2.1 Energy Sources in Transport

From the physical point of view the term “energy” is defined as an ability of a physical system to perform work, i.e. it is the work contained in the physical system. Moreover, it can be said that it is a measure of all forms of a mass motion. Since even a not moving mass acquires a certain measure of energy it is essential to note that also a potential motion of the mass, i.e. not only the performed motion itself, may be considered as energy. Thus, a more accurate definition would be that energy is a measure of all forms of a motion or a potential to perform a motion.

Mostly we speak about a kind of energy by a physical field (electromagnetic energy, energy of gravitation field, light energy, radiation energy, etc.).

The law of conservation of energy in physics states that a closed physical system’s energy is constant. In other words: energy is neither created nor destroyed, but it is transformed from one form of energy to another form or other forms of energy. We may also say: the change of a system’s energy equals the work performed or consumed by this system.

Energy transforms to work, and vice versa. If a system moves from the rest to the motion, or vice versa, and there is no mechanic work added or removed from it, the sum of a potential and kinetic energy remains unchanged.

The information above implies the energy cannot be created; it can only be transformed to other forms. Thus, in application of these relations to energy in transport and transport means we may state that the production of electric energy is a transformation of other forms of energy (by sources, e.g. kinetic energy of a water flow, solar energy, heat energy of coal, nuclear energy, etc.) to electric energy. Subsequently when an electric vehicle moves this electric energy is transformed to a mechanical energy of the given vehicle’s motion. When a car with a combustion engine moves, the chemical energy bound in a hydrocarbon fuel (gasoline and diesel) is transformed to a mechanical energy of the car’s motion. Of course, there are some losses in these processes so during the transformation to the mechanical energy the biggest loss part is changed to a thermal energy (engine and other car parts heating).

The SI unit of energy is a joule (1 J). It is a relatively small unit to express the energy consumption in transport. Its multiples, such as kJ, MJ, GJ are used, e.g. with regard to a vehicle’s consumption. In case of statistic data on bigger consumed volumes we use PJ and TJ units. There exists an equivalent unit—kWh, mainly in context of the electric energy. The following conversion is true: 1 kWh = 3,600,000 J = 3,600 kJ = 3.6 MJ. The previous statement makes the value of 1 J clear. In order to represent it closer we may mention an average value of incident solar radiation onto the Earth’s surface which is approx. 1.36 $kJ/m^2/s$; and thus, the power is 1.36 kW/m^2.

2.2 The Energy Consumption by Transport Means

The energy consumption by transport means is most often represented with the consumption of an energy kind (fuel or propellant) of a given transport means, vehicle. The term "fuel" or "propellant" results from the fact that since the past up to the present day it has been liquid hydrocarbon fuels to the greatest extent, and gas hydrocarbon fuels to a lesser extent. Nowadays a vehicle drive by electric energy is promoted more and more. It would be improper to use the term "fuel" in connection with such vehicles; it is replaced with a general name "energy consumption" used in real life. However, for the sake of an accurate naming convention it is necessary to use the term "electric energy consumption" [32].

"Consumption" in context of road motor vehicles expresses the amount of the used (consumed) fuel or energy for their operation. The energy consumed (or released while burning a fuel) is used to provide the operation of main and supporting functions of a vehicle needed for fulfilling the goals the vehicle is used for. Currently road motor vehicles ("vehicles") use various kinds of fuels, as it has already been mentioned, however, besides electrically powered vehicles the term "road motor vehicle" also represents such a vehicle which is equipped with a thermal combustion piston engine with an inner discontinuous combustion and a straight-line reciprocating motion of the piston ("engine"), transforming the energy of chemical bindings of hydrocarbon fuels through combusting a mixture of fuel and air to the mechanical energy used for the operation of the vehicle (drive, or other actions and additional activities) [32].

2.3 Energy Bound in Fuels

A physical quality of fuels, a so called "lower heating value"—labelled H_u (known as a net calorific value, too) is a value including a released energy from a fuel when burned under adiabatic conditions with the pressure of 101.325 kPa provided that resultant products of combustion will cool down to the temperature they had before the burn, but the water vapour occurring in burned gases is in a gaseous state. In simpler words, it is the energy included in the fuel which may be acquired within its burning without water vapour condensation. This physical value is used to compare the energy included in fuels, and it also appears using the terms like energy content [33] or energy density. The term "energy density" is used due to units it is expressed in, i.e. J g^{-1} (amount of energy/mass of fuel), however, there in real life multiples of the following basic units are preferred: kJ kg^{-1} or MJ kg^{-1}.

Table 14 shows big differences in the energy content of fuels. Specifically, there exists a six-fold difference between the fuel "richest" in energy, and the "poorest" one. However, on the basis of these values we cannot conclude what fuel is really the most energy effective in its utilisation in transport means. The cause lies in the fact that each of them is burned in the engine with a different efficiency, and thus it is not possible to utilise its energetic potential with an equal division in all of them.

Table 14 Energy content of fuels in transport [2]

Fuel	Energy content (lower heating value) [MJ/kg]
Hydrogen	120.1
Biogas	50
Methane	50
Natural gas (CNG or LNG)	45.1–49.2
Liquefied petroleum Gas (LPG)	46.0
Synthetic diesel	44
Hydrogenated refined vegetable oil	44
Motor gasoline	43
Diesel fuel	43
Biodiesel	37
Pure Vegetables oil	37
Bioethanol	27
Biomethanol	20

Examples include efficiencies of current combustion engines used in road vehicles [34, 35]:

- spark-ignition engine (motor gasoline) 30–40%,
- compression ignition engine (diesel fuel) 40–50%.

The values of efficiency mentioned above prove the highest possible achievable value which appears in a close zone of the engine burden and operation revolutions. So, during a regular operation of the vehicle it is achieved only seldom, and the average value of the operation efficiency is lower.

Therefore, it is required to come out from data on average consumptions of vehicles in operation, which considers the mode of driving (operation), and thus the work (energy) which the engine has to spend, i.e. burn the fuel [36]. Such a comparison is given in Table 16 upon evaluating the energy intensity of electric energy when used in transport modes.

2.4 Electricity—An Energy Source in Transport

Recently the electric traction has become a more and more used alternative to common fuels especially in road transport. Strategic goals and initiatives of developed countries' governments support the implementation of electro-mobility as one of instruments in the area of reducing the energy intensity and carbon footprint of human activities.

To assess the energy intensity of a fuel and electrical energy consumption in transport we can use two forms of expressing their impacts on the society and the environment:

1. Impacts of a social nature, in the form of:
   (a) LCA principle, i.e. life cycle analysis,
   (b) WtW principle (well to wheel) which takes into account both the direct and indirect consumption of energy.
2. Impacts of a regional (closer) nature, in the form of:
   (a) TtW principle (tank to wheel) which takes into account the direct consumption of energy only.

The LCA principle considers the energy consumed by the vehicle's operation on one hand, and its production, distribution and storage along with the energy consumed during the transport means production and its maintenance and repairs during the whole life cycle on the other hand.

The WtW principle considers the energy consumed by the vehicle's operation as well as the production, distribution and storage of this energy.

The TtW principle only considers the energy consumed by the direct operation of the vehicle. For example, it is the consumption of fuel or electric energy during the vehicle motion.

The energy and emission factor (WtW) consider partial losses in the production and distribution of electric energy in the chain:

1. The structure of energy sources used in the production of electric energy.
2. Efficiency of the electric energy production from individual sources.
3. Efficiency of the electric energy transfer (distribution) to an end consumer.

This implies that the effectiveness (efficiency) of electric energy is directly dependent on the technology of the electric energy production, on the structure and shares of individual sources, and on efficiency of its distribution [37].

The energy efficiency within the electric energy production can be calculated as a weighted arithmetic mean of shares of primary sources and efficiencies during the electric energy production of individual sources. The weights of values represent shares of individual sources. The values of efficiency were selected per the national regulation [38]. The produced energy gets to the consumer through a transmission grid. This process does not run without any losses and inevitable energy consumption to operate this system. For example, the transmission grid and transformer system of the Slovak Republic manifest the efficiency of approx. 93%.

Net losses in the transmission grid are evaluated as a difference between the electricity volume which enters the transmission grid, and the electricity volume which is output from the grid and reduced by own consumption of electricity of the transmission grid provider. The losses in the transmission grid are quadratically dependent on the volume of transmitted electricity. These losses of the net transmission and transformation of electricity were on the level of 1.08% in the Slovak Republic in 2017 [39].

Last losses during the transmission of the produced electric energy onto the vehicle's wheels are own losses at the transmission:

(a) from the transmission line through a collector and a control system of the vehicle (in case of tractive vehicles powered from the upper line, trolleys)—the efficiency of this process is approx. 90%,
(b) of electricity through a charging device into the vehicle's accumulators (in case of battery electric vehicles and plug-in hybrids)—the transmission efficiency decreases with an increasing speed of charging.

The overall energy efficiency of the supplied electric energy for a transport means can be determined with the formula [10]:

$$\eta = \eta_{\mathrm{Pr}od} \cdot \eta_{Trans} \cdot \eta_{Veh} = \frac{\sum(\eta_{Si} \cdot p_{Si})}{\sum p_S} \cdot \eta_{Trans} \cdot \eta_{Veh}(-), \tag{1}$$

where

η	overall energy efficiency [−]
η_{Prod}	efficiency of the electric energy production [−]
η_{Trans}	efficiency of the electric energy transmission [−]
η_{Veh}	efficiency of the transport means [−]
η_{Si}	efficiency of a specific primary source [−]
p_{Si}	share of a specific source in the electric energy production [−]
p_S	sum of partial shares of individual sources [−]

For the purpose of this study, following countries are being introduced: Austria (AT), Czech Republic (CZ), Germany (DE), Hungary (HU), Poland (PL), Slovakia (SK) and Slovenia (SI) [40].

This European Standard EN 16258:2012 specifies the methodology how to calculate and declare the energy intensity and GHG production in relation to transport operation. It defines general principles, definitions, system boundaries and methods of calculation in the given issue. The standard does not consider only the production of the secondary emissions and energy consumed during the combustion of the fuel (energy conversion from fuel to mechanical energy), but also primary, incurred in the extraction, production and distribution [40].

Tank-to-wheels energy factor (e_t) for electricity equals 3.6 MJ/kWh, and tank-to-wheels emission factor (g_t) for electricity is equal to zero [41]. The electric power generation technology, composition and share of primary sources and distribution effectiveness have a direct influence on the effectiveness of electricity (Fig. 29).

Values of effectiveness were chosen from the International Atomic Energy Agency Bulletin [42]. The energy generated is distributed to the grid through the transmission branch system. This process is operated with some losses (energy branch consumption). Electric power distribution effectivity in the grid of the Central Europe countries

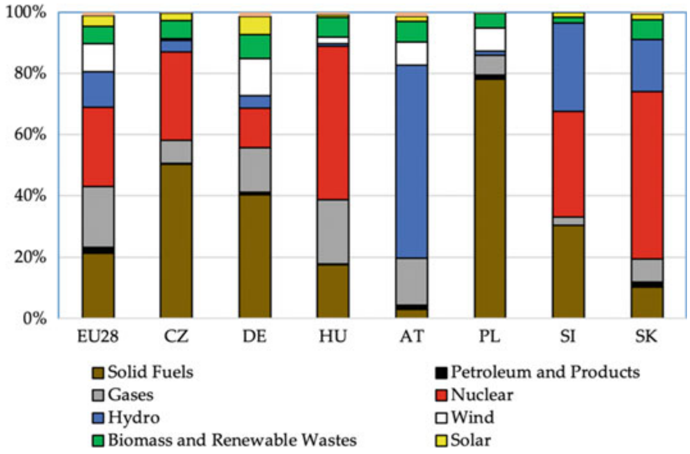

Fig. 29 Share of primary sources in the production of electric energy in selected countries in 2016 [40]

was at the level from 84% (Poland) to 93% (Slovenia) [40]. The total energy effectiveness of consumed electric power in transport is calculated according to the Eq. 1. According to the above-mentioned facts and their real composition in Central Europe countries, the electric power generation is usually burdened with the effectiveness from 31% (Hungary) to 63% (Austria). As far as the electricity production in the Central European countries is concerned, the values from the Decree regulating the lowest efficiencies of operated power plants were used as input data (Fig. 30) [43].

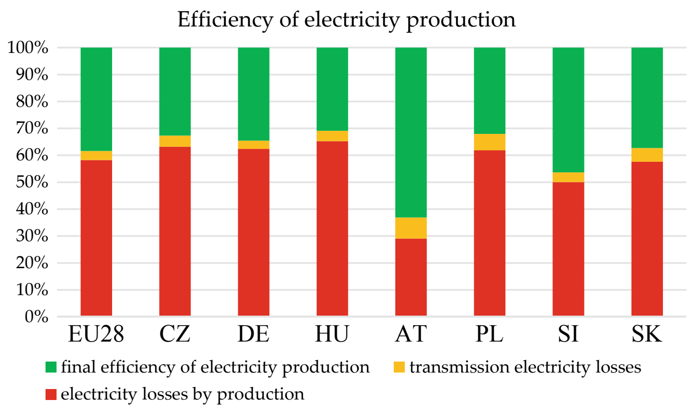

Fig. 30 The electricity production efficiency [40]

2.5 *Evaluation of Energy Intensity and Greenhouse Gas Production*

The energy intensity and the effectiveness of electric vehicles operation in selected countries can be determined on the basis of the effectiveness of the electric energy production.

Along with the combustion of fuels in combustion engines and consumption of electric energy in electromotors there arise gas emissions in the form of greenhouse gases. Their volume depends on the following:

(a) volume of the energy consumed for the production and distribution of fuels and electricity, as well as for their direct combustion in transport means,
(b) emission intensity of individual fuels and site of the electricity production.

The Kyoto Protocol solves the issue of emissions of these six kinds of greenhouse gases:

1. carbon dioxide (CO_2),
2. methane (CH_4),
3. nitrous oxide (N_2O),
4. hydrofluorocarbons (HFC),
5. perfluorocarbons (PFC),
6. sulphur hexafluoride (SF_6).

There in the area of transport and the fuel and electricity production, carbon dioxide, methane and nitrous oxide feature the highest occurrence. The remaining three gases represent only a very small share.

With regard to the volume of energy consumed during the operation of transport means and in consideration of emission factors of these energy sources it is possible to determine the production of greenhouse gases based on their operation. If the principle W-t-W is applied, then it is a comparative indicator applicable to a mutual comparison of different countries, types of transport or types of transport means (Table 15) [44, 45].

Table 16 lists results of the energy consumption and the greenhouse gas production from the operation of a passenger car, medium class, with typical sizes and power parameters. Data regarding the consumption is taken from the declared data provided by the vehicle's manufacturer (selected specific makes and types of vehicles on the basis of the highest frequency of registered vehicles) on its fuel and energy consumption measured based on the driving cycle NEDC and energy and emission factors of electricity and fuels stated above and obtained from [41, 46].

Table 16 implies we cannot generally state that the operation of vehicles with an electric traction is more acceptable for the environment than the operation of vehicles with a combustion engine. The evaluation of both direct and indirect factors leads to the statement that it is the kind of fuel which decides on the energy intensity of the vehicle's operation, and it is the country of the electricity production which is important in case of the electric traction. The results imply that the operation of an

Table 15 Energy intensity and GHG production of cars with different propulsion [41, author]

Fuel	T-t-W energy		W-t-W energy		T-t-W emissions	W-t-W emissions
	MJ/kg	MJ/l	MJ/kg	MJ/l	gCO_{2e}/MJ	gCO_{2e}/MJ
Gasoline	43.2	32.2	50.5	37.7	75.2	89.4
Ethanol	26.8	21.3	65.7	52.1	0	58.1
Gasoline/ethano mixture 95/5	42.4	31.7	51.4	38.4	72.6	88.4
Diesel fuel	43.1	35.9	51.3	42.7	74.5	90.4
Biodiesel	36.8	32.8	76.9	68.5	0	58.8
Diesel/biodiesel mixture 95/5	42.8	35.7	52.7	44.0	71.0	88.8
Liquefied petroleum gas (LPG)	46.0	25.3	51.5	28.3	67.3	75.3
Compressed natural gas (CNG)	45.1		50.5		59.4	68.1

Table 16 Energy intensity and GHG production of cars with different propulsion [40]

Energy source	FC and FE (l, kg, kWh/100 km)	W-t-W	
		Energy consumption (MJ/100 km)	Production of CO_{2e} (g/km)
Gasoline	5.6	211	161
CNG	4.4	220	135
Diesel	4.4	188	143
Electricity[a]	20	114–233	28–161
Hybrid[b]	4	151	115

[a]This value varies according to the country of the vehicle operation or electric power origin
[b]It depends on regime of the vehicle operational velocity profile (urban, rural, motorway)

electric vehicle may be much more energy efficient and less emission demanding, however, this is also true the other way around.

A vehicle equipped with an ICE engine produces less GHG when compared to an e-vehicle powered with electricity and produced in Poland, for example. And also, the energy efficiency of an ICE driven car is higher than e-vehicle operated for example in Hungary.

3 Emissions of Greenhouse Gases from Transport Services

Transport is one of the biggest producers of greenhouse gases (GHG). The volume of produced emissions may be expressed as an equivalent to emissions of carbon dioxide (CO_{2e}), which expresses the volume of emissions of CO_2, representing the same potential of global warming as a mixture of real greenhouse gases—carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [47].

According to Vaishnav [48] international transport (mainly maritime and air transport) represents one of the fastest developing sectors of human activity in relation to the production of greenhouse gas emissions.

Ližbetin et al. [45] deal with the issue of greenhouse gas emissions production by the road freight transport sector. These emissions affect the structure of the ozone layer and contribute to the greenhouse effect that causes global warming-issues that are closely associated with changing weather patterns and extreme weather events. Attention is drawn to the contradictions linked to FAME (Fatty Acid Methyl Esters) biofuels, namely the fact that although their use generates almost zero greenhouse gas emissions, their production requires high levels of energy consumption.

The article by Ivkovic et al. [49] specialises in the production of greenhouse gas emissions in context of long-distance passenger transport, in particular road and air transport. The goal of their research was the creation and selection of an appropriate methodology for modelling the cost estimation of GHG emissions in road and air transport sector for Republic of Serbia as well as the application of the methodology regarding the detailed calculation by transport mode and sub modes.

3.1 Declaration of Greenhouse Gas Emissions from Transport Services in Europe Per STN EN 16258 Standard

The environmental acceptability of vehicles' operation is currently a significant criterion for the quality of transport services. Carriers are more and more required to declare the impact of their activity on the environment through the issue of documents containing specific volumes of pollutant emissions from transport operation, mainly emissions of carbon dioxide (CO_2) as the most widespread greenhouse gas. Various approaches to the calculation of the energy consumption and greenhouse gas (GHG) emissions production from the transport operation have led to the need for a unified methodology of their calculation.

On 8 September 2012 the European Committee for Standardization (CEN) approved the European standard EN 16258 *Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passenger transport).* In September 2013 the standard was adopted in Slovak language into the Slovak Standardization System under the label ***STN EN 16258:2013*** under the name of ***Methodology for Calculation and Declaration of Energy Consumption and GHG Emissions from Transport Services (freight and passenger transport)***.

The aim is for the standard to be widely applicable within the entire transport industry and accessible to various groups of users.

The application of the standard provides a common approach to the calculation and to the declaration of energy consumption and emissions for transport services regardless the demandingness of the transportation and transportation process technology. The standard secures that declarations feature a greater consistency and transparency, and that the consumed energy and produced emissions match the burden or occupancy of vehicles.

3.2 Direct and Indirect Energy Consumption and Emissions Production

The standard sets a methodology and requirements for the calculation and reporting of the energy consumption and emissions of greenhouse gases (GHG) from transport services. The first issue of the standard is primarily focused on the energy consumption and emissions of greenhouse gases in connection with transport means (used on the land, in water and in air) during the operation stage of the lifecycle. However, in calculations of the energy consumption and emissions related to vehicles we also need to consider the energy consumption and emissions related to energy processes for fuels and/or electricity used by vehicles (including the production and distribution of propellants). It ensures that the standard takes on the approach "well-to-wheel" while conducting the calculations and declaring the energy consumption and the greenhouse gas production for transport service users.

Well-to-Wheel (WtW) is an approach based on monitoring the energy consumption and emission production from the energy generation itself up to its final consumption. It comprises two parts:

- ***Well-to-Tank (WtT)***—the energy consumption and the emission production during the energy generation,
- ***Tank-to-Wheel (TtW)***—the energy consumption and the emission production during the vehicle operation.

Way of Expressing the Volume of Greenhouse Gas Emissions

In the calculations of the volume of greenhouse gas emissions the standard considers the unit of CO_{2e} (an equivalent to carbon dioxide), since carbon dioxide represents the biggest share in the greenhouse gas production. The value of CO_{2e} determines the rate of individual greenhouse gases impact on global warming using a recalculation per the volume or concentration of CO_2, which would have similar impacts.

In comparison with the current approach to reporting of the volume of greenhouse gas emissions the standard introduces:

- the unification of the calculation methodology using unified values of emission factors (unified values of emission factors can be found in Table 17),
- the calculation of the production of all greenhouse gas emissions,

Table 17 Emission factors of propellants

Kind of fuel	Emission factor of greenhouse gases					
	Tank-to-wheels (gt)			Well-to-wheels (gw)		
	gCO_{2e}/MJ	$kgCO_{2e}$/kg	$kgCO_{2e}$/l	gCO_2CO_{2e}/MJ	$kgCO_{2e}$/kg	$kgCO_{2e}$/l
Gasoline	75.2	3.25	2.42	89.4	3.86	2.88
Ethanol	0	0	0	58.1	1.56	1.24
Gasoline/ethanol mixture 95/5	72.6	3.08	2.30	88.4	3.74	2.80
Diesel Fuel	74.5	3.21	2.67	90.4	3.90	3.24
Biodiesel	0	0	0	58.8	2.16	1.92
Diesel/biodiesel mixture 95/5	71.0	3.04	2.54	88.8	3.80	3.17
Liquefied petroleum gas (LPG)	67.3	3.10	1.70	75.3	3.46	1.90
Compressed natural gas (CNG)	59.4	2.68		68.1	3.07	
Aviation gasoline (AvGas)	70.6	3.13	2.50	84.8	3.76	3.01
Aviation gasoline (Jet B)	70.6	3.13	2.50	84.8	3.76	3.01
Aviation paraffin oil (Jet A1 and Jet A)	72.1	3.18	2.54	88.0	3.88	3.10
Heavy fuel oil (HFO)	77.7	3.15	3.05	84.3	3.41	3.31
Marine diesel oil (MDO)	75.3	3.24	2.92	91.2	3.92	3.53
Marine gas oil (MGO)	75.3	3.24	2.88	91.2	3.92	3.49

Source Worked out by the author based on [50]

- the recalculation per the unit of CO_{2e}—this is a consideration of both direct and indirect emissions from the vehicle operation which will allow for an objective comparison of their impacts on the environment.

3.3 Principles of Calculating the Greenhouse Gas Emissions Per STN EN 16258 Standard

For the sake of the calculation it is required to know operation characteristics of vehicles and transport services, such as the vehicle consumption, transportation distance, number of km driven with an unladen or unoccupied vehicle, number of carried people, and occupancy of the vehicle [51, 52]. The calculation should contain the following characteristics of greenhouse gas emissions:

- WtW greenhouse gas emissions (G_W),
- TtW greenhouse gas emissions (G_t).

Calculations for a Vehicle Operation System

In case the transport service comprises multiple sections, it is necessary to identify the vehicle operation system (VOS) for individual sections, namely the number and categories of operated vehicles including the time of their operation.

The calculation comes out from the identification of the vehicle consumption in a specific VOS. The recalculation of the total fuel consumption for the VOS per the volume of the energy consumption and greenhouse gas emissions must be done using these formulae:

- for WtW greenhouse gas emissions of the VOS:
- $G_W(VOS) = F(VOS).g_W$ (2)

- for TtW greenhouse gas emissions of the VOS:
- $G_t(VOS) = F(VOS).g_t$ (3)

where

- F(VOS) is the total fuel consumption used for the VOS (e.g.: F(VOS) equals 5,000 l of diesel),
- g_W is the well-to-wheels emission factor of greenhouse gases of the used fuel (e.g.: diesel, $g_W = 3.24$ kgCO_{2e}/l),
- g_t is the tank-to-wheels emission factor of greenhouse gases of the used fuel (e.g.: diesel, $g_t = 2.67$ kgCO_{2e}/l).

The calculation requires values of energy and emission factors of greenhouse gases given in the appendix A of STN EN 16258 standard, see Table 17.

Calculations for a Section of a Transport Service

In case the realised transport service comprises multiple sections (various customers, various numbers of carried passengers, distance run with an occupied and an empty vehicle, etc.) it is necessary to perform a recalculation of the energy consumption and emissions per the section. The calculation is performed as follows:

- The VOS used to realise transport services in the given section is identified.
- The total consumption of the VOS is quantified.
- Emissions for the VOS are calculated using the relations (2) and (3).
- The share of emissions applicable to the transport service section being solved (a dimensionless number) is calculated as a ratio of the performance applicable to the transport service section and the performance of the vehicle operation system:

$$\mathrm{S(section)} = \mathrm{T(section)}/\mathrm{T(VOS)} \tag{4}$$

Afterwards this share is used to calculate greenhouse gas emissions for the transport service section being solved:

$$\mathrm{G_W(section)} = \mathrm{G_W(VOS)}\,.\,\mathrm{S(section)} \tag{5}$$

$$\mathrm{G_t(section)} = \mathrm{G_t(VOS)}\,.\,\mathrm{S(section)} \tag{6}$$

The performance of the vehicle operation system (T(VOS)) and the performance for the transport service section (T(section)) must be in the same unit expression. The standard recommends to use a transportation performance for both passenger and freight transport, i.e. a product of the number of carried people and actual transportation distance in the units of passenger-kilometre there in passenger transport, and a product of the volume of transported goods and actual transportation distance in the units of tonne-kilometre there in freight transport.

3.4 Structure and Content of the Declaration Regarding the Energy Consumption and GHG Emissions

EN 16258 standard does not dictate any form of the declaration, however, it defines requirements on its content. A user of the standard may use any medium for the sake of the declaration to its receiver; the medium provides explicit results and related details for the calculation, e.g. a web page. Published for example in [8].

The declaration regarding the energy consumption and greenhouse gas emissions from transport services must contain:

(a) *four results* (E_W, G_W, E_t, *and* G_t) calculated using the given procedure (in case of energy in J, or MJ or GJ units, in case of emissions of CO_{2e} in g, or kg or t units),
(b) *additional information* which should (among other things) contain also the following:

- transparent description of the method used; in case of using energy consumption factors and emission factors other than those stated in appendix A of the standard they are required to be justified, and also it is necessary to justify the usage of predefined values,
- basic description of the transport service (the source and the destination of the route, the number of carried persons),
- description of the operation during the transport service performance,
- the vehicle operation system used for each section,

- the size of the fleet, categories of vehicles,
- recalculated resultant values of the energy consumption and greenhouse gas emissions per the performance unit,
- another information needed to understand the method used.

It is also possible to work out a so-called simplified declaration which may comprise two parts. The first part contains the WtW value of greenhouse gas emissions (G_W) from the transport service, and a reference to the option of obtaining the remaining three values (Ew, E_t and G_t), e.g. on a web page. The second part of the declaration contains the remaining three results and additional information; the second part of the declaration is available to its recipient for an appropriate period.

Formally, the declaration can be created using the following standard: STN CEN/TR 14310:2003 Freight transport services [53]. The promulgation and reporting of environmental performance in freight transport network. The standard is compatible with ISO standards, series 14,000, regarding environmental requirements in connection with environmental management systems (EMS). *The aim of the standard is to provide guidance for preparing (creating) environmental declarations and reports*. It contains recommendations on the content and structure of the documentation, and evaluation of the impacts of freight transport on the environment [54, 55].

3.5 A Comparative Analysis of Emission Factors of Direct Greenhouse Gas Emissions in Europe and All Over the World

One of the most important elements for the calculation of greenhouse gas emissions is the emission factors. These emission factors enable us to estimate the volume of produced emissions based on the input data (such as the consumption of propellants). These emission factors of greenhouse gases are often provided in an equivalent to CO_2, a so called CO_{2e}. It means that CH_4 and N_2O are recalculated per the equivalent to CO_2 which should have similar impacts on the environment and the greenhouse effect. The majority of emission factors in various databases enables to calculate the volume of greenhouse gases separately, too.

There are various sources of emission factors of greenhouse gases in the world:

- EN 16258—Europe/2012,
- Department for Environment, Food and Rural Affairs ("DEFRA")—United Kingdom/2018,
- Environmental Protection Agency ("EPA")—USA/2018,
- Greenhouse Gas Inventory Office of Japan ("GIO")—Japan/2016,
- Department of the Environment and Energy (national emission factors—"NGA")—Australia/2018,
- Ministry for the Environment (Guidance for voluntary greenhouse gas reporting)—New Zealand/2016.

All databases of emission factors of greenhouse gases mentioned above enable to calculate the value of CO_{2e}. Specific values of greenhouse gases (CO_{2e}, CH_4, and N_2O) are introduced in all sources except for EN 16258 standard which is focused on CO_{2e} and the energy consumption.

The chart in Fig. 31 illustrates a comparison of emission factors of direct greenhouse gas emissions for a standard diesel fuel without using any biocomponent in different parts of the world. We can see slight differences in values of $kgCO_{2e}/l$ used for the calculation of greenhouse gas emissions.

Likewise, we may state that the biggest value of CO_{2e} is noted in the database of NGA (2.7198 $kgCO_{2e}/l$) and a negligibly smaller one in New Zealand. On the other hand, the smallest value is noted by GIO on the level of 2.6515 $kgCO_{2e}/l$. EN 16258 standard used by many emissions calculators in the EU lists the value of 2.67 $kgCO_{2e}/l$, which is almost identical to emission factors introduced by DEFRA in the United Kingdom.

All of these emission factors are related to so called direct emissions ("TTW"), which means these are emissions arising during the vehicle operation. Detailed emission factors of individual greenhouse gas emissions are presented in Table 18.

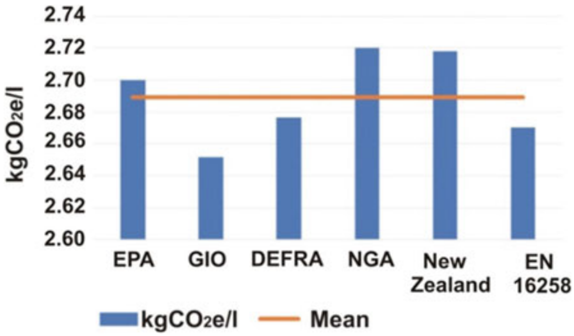

Fig. 31 A Comparison of greenhouse gas emission factors from diesel fuel used in the world—expressed in CO_{2e}

Table 18 Emission factors of individual greenhouse gases of diesel fuel

Diesel (100%) TTW	Density kg/l	$kgCO_{2e}/kg$	$kgCO_{2e}/l$	$kgCO_2/l$	$kgCH_4/l$	kgN_2O/l
EPA	0.8432	3.2017	2.6998	2.6972	0.000008	0.000008
GIO	0.8832	3.0021	2.6515	2.6195	0.000026	0.000105
DEFRA	0.8375	3.1900	2.6717	2.6502	0.000024	0.000070
NGA	x	x	2.7198	2.6982	0.000092	0.000064
New Zealand	0.8401	3.2352	2.7179	2.672	0.000142	0.000142
EN 16258	0.8320	3.2100	2.6700	x	x	x
Mean	0.8487	3.1678	2.6885	2.6674	0.000058	0.000078
Extent of variation	0.0512	0.2331	0.0683	0.0787	0.000133	0.000134

Table 19 Emission factors of individual greenhouse gases of diesel fuel B5

Diesel B5 TTW	Density kg/l	$kgCO_{2e}/kg$	$kgCO_{2e}/l$	$kgCO_2/l$	kgCH4/l	kgN_2O/l
EN 16258	0.8350	3.0400	2.5400	×	×	×
EPA	0.8747	2.9321	2.5648	2.5623	0.000007	0.000007
Defra	0.8390	3.0264	2.5391	2.5187	0.000022	0.000066
Mean	0.8496	2.9995	2.5480	2.5405	0.000015	0.000037
Extent of variation	0.0397	0.1079	0.0168	0.0436	0.000015	0.000059

Table created from the data: EPA (2018), DEFRA (2018), EN 16258

Table created from the data: EPA (2018), DEFRA (2018), GIO (2016), NGA (2018), EN 16258, New Zealand emission factors.

When compared to other kinds of fuels these sources of emission factors manifest certain limitations, since not all of them provide emission factors for different kinds of fuel used by vehicles of road freight transport. Mostly these are fuels with a various share of the biocomponent, or vehicles powered with compressed natural gas (CNG) or liquefied petroleum gas (LNG).

Emission factors of CO_{2e} when diesel fuel B5 (5% share of the biocomponent) is used show values from 2.5391 up to 2.5648 kg CO_{2e}/l. The biggest value was manifested by the emission factor of EPA, and on the contrary, the smallest value was manifested by DEFRA which was almost identical to the emission factor given in EN 16258 standard. The mean value is on the level of 2.5480 kg CO_{2e}/l. Detailed emission factors of individual greenhouse gases are presented in Table 19.

3.6 *Case Study—Application of Emission and Energy Calculator Per STN EN 16258 Standard*

A suggested calculator of the energy consumption and emissions is used for a sample calculation for direct transportation by means of road transport. The calculator was suggested and tested within [9]. Namely the direct transportation on Bratislava—Žilina—Bratislava route is realised; the vehicle combination features an average consumption of 31 l/100 km, effective weight of the combination is 26 t, type of the vehicle: a lorry of N_3 category, a towed vehicle of O_4 category. Parameters of the vehicle: Man TGX 26.440 with a trailer SVAN CHTP 18-22, 324 kW, EURO V, year of manufacture: 2012; the vehicle was fuelled up with diesel fuel with the biocomponent content of 6%. The average consumption of the vehicle combination is 30.72 l/100 km.

The input data for the calculation of greenhouse gas emissions and the energy consumption for direct transportation is presented in Table 20.

Table 20 Input data for the calculation of greenhouse gas emissions and the energy consumption for direct transportation

Information on the carrier	
Business name of the carrier	Anton transportér, a contract carrier
Domicile address	Bratislava—Ružinov
Street	Ivanská cesta
ZIP code	821 04
Contact person	Anton Transportér
Phone no.	0904 XXX XXX
Date	14.10.2019
Input data for the calculation	
Transportation session	Bratislava, Ivanská cesta—Žilina, Ul. Milana Rastislava Štefánika—Bratislava, Ivanská cesta
Driving performance (km)	382
Vehicle, engine power, emission limit, year of manufacture	Man TGX26.440 with a trailer SVAN CHTP 18-22, 324 kW, Euro V, 2012
The average consumption determined by the vehicle's manufacturer (l/100 km)	30.72
Total weight of the vehicle/vehicle combination (t)	40
Weight of goods (t)	3.84
Kind of Fuel	Diesel
Share of Biocomponents (%)	6

Source Worked out by the authors based on [52]

An own calculation will be performed for the provided input data. The results of the calculation are presented in a table form within an output report (see Table 21).

The calculator also allows for creating (exporting) the declaration with calculated values of greenhouse gas emissions and energy consumption in order to provide it to the order party.

The utilisation of multiple kinds of transport within the logistic chain, the operation of various categories of vehicles which are acceptable to a different extent from the point of view of their age and environmental burden, the existence of multiple vehicles manufactures, various operation conditions as well as the impact of a driver on the economy of operation were limiting factors which led to the need to generalise the method of calculating the energy consumption and volume of greenhouse gas emissions from the transport operation. A significant contribution lies in the unification of energy and emission factors which results in the possibility to objectively assess the energy intensity and environmental impacts of various transport systems. Another considerable aspect is the indirect consumption and indirect greenhouse gas emissions in relation to the production of energy for the transport system.

Table 21 Results of the calculation of greenhouse gas emissions and the energy consumption for direct transportation

Indicator	Characteristics
Transportation session	Bratislava, Ivanská cesta—Žilina, Ul. Milana Rastislava Štefánika—Bratislava, Ivanská cesta
Driving performance (km)	382
Vehicle, engine power, emission limit, year of manufacture	Man TGX26.440 with a trailer SVAN CHTP 18-22, 324 kW, Euro V, 2012
Indicator	Result of the Calculation
Average consumption (l/100 km)	30.72
Total weight of the vehicle/vehicle combination (t)	40
Weight of goods (t)	3.84
Kind of fuel	Diesel
Share of biocomponents (%)	6
Consumption of propellants (l)	117.35
The volume of emissions of CO_2 during the transportation (gt($kgCO_{2e}$/l))	294.5495
The volume of emissions of CO_2 during the transportation (gw($kgCO_{2e}$/l))	370.8273

Source Worked out by the authors based on [52]

Currently the commercially available emission and energy calculators do not allow the calculation of emissions per STN EN 16258 standard, or they do not allow the export of declarations in a required structure. Besides the calculation of greenhouse gas emissions and energy consumption for the direct road transport a suitable calculator should also enable the calculation of emissions for a distribution task and issue of declarations by individual customers (delivery points) within the distribution task.

The calculation of greenhouse gas emissions from distribution tasks is dealt with in articles by Kellner et al. [56] and Jevinger et al. [57].

The paper [56] studies how to allocate the GHG volume of a transportation process (delivery tour) to the single shipments moved by the process. Jevinger et al. [57] published the paper that presents and evaluates a new method for how emissions from freight transport routes with single or several points of loading and unloading can be allocated to individual consignments.

The calculation of emissions for haulage and distribution tasks may be performed on the basis of a modification of a section principle recommended with EN 16258 standard, while this modification comes out from recommendations introduced in the manual of CLECAT [58], and it was published in [59], too.

Moreover, commercial emission calculators do not enable a calculation of external costs from transport operation, i.e. a financial statement of the transport operation impact on the environment. For the sake of the calculation it is possible to use values of external costs of individual emissions stated for example in [60]. Such a type of a calculator of greenhouse gas emissions as well as of external costs is published in [61].

When looking into the future we may expect a unification of emission factors for other harmful pollutants of exhaust gases, or harmful pollutants from the production of energies and propellants, using the pattern of greenhouse gas emissions due to objectivity and achieving the same results of calculation of harmful pollutants emissions while using different emission calculators.

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Logistic Flow Control System in Green Supply Chains

Nikita Osintsev, Aleksandr Rakhmangulov, Aleksander Sładkowski and Natalja Dyorina

Abstract The effective concept implementation of sustainable development in logistics and supply chain management is based on the use of management decision-making methods for changing the parameters of logistics flows. Decisions should be made based on the measurement and evaluation of the parameters and indicators of these flows. The complexity of managing green supply chains is associated with insufficient knowledge of the system of logistics flows indicators and parameters, as well as in the absence of methods for their comprehensive assessment. In the present work, an original system of indicators (indicators and parameters) of logistic flows in green supply chains is proposed. Managed parameters of logistic flows are identified, the change of which ensures the principles implementation of the sustainable development concept. The use of the fuzzy AHP-TOPSIS method for evaluating the performance of logistics flows in green supply chains is considered. A fuzzy model for managing the parameters of logistics flows has been developed. Changing the parameters of logistic flows in order to achieve the goals of the sustainable development concept is proposed to be carried out using the original system of green logistics instruments. The work presents a calculation implementation example in the logistics flow control system of the procedure for selecting green logistic instruments.

Keywords Sustainable development · Green logistics · Transport systems · Green supply chain management · Logistics flows · Indicators · Fuzzy approach · AHP-TOPSIS · Decision-making

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1 Sustainable Development Problems of the Global Transport System and Supply Chains

The development of international trade in the context of globalization leads to an increase in world trade, the expansion and complication of the commodity nomenclature, and a change in the geographical structure of international trade. The main indicators of foreign economic activity (export and import) of countries that have a significant impact on world trade (USA, China, Germany, etc.) demonstrate a steady upward trend (Fig. 1) [1].

The world trade development is facilitated by the intensive implementation of the One Belt—One Road Initiative [2], based on the economies integration of 65

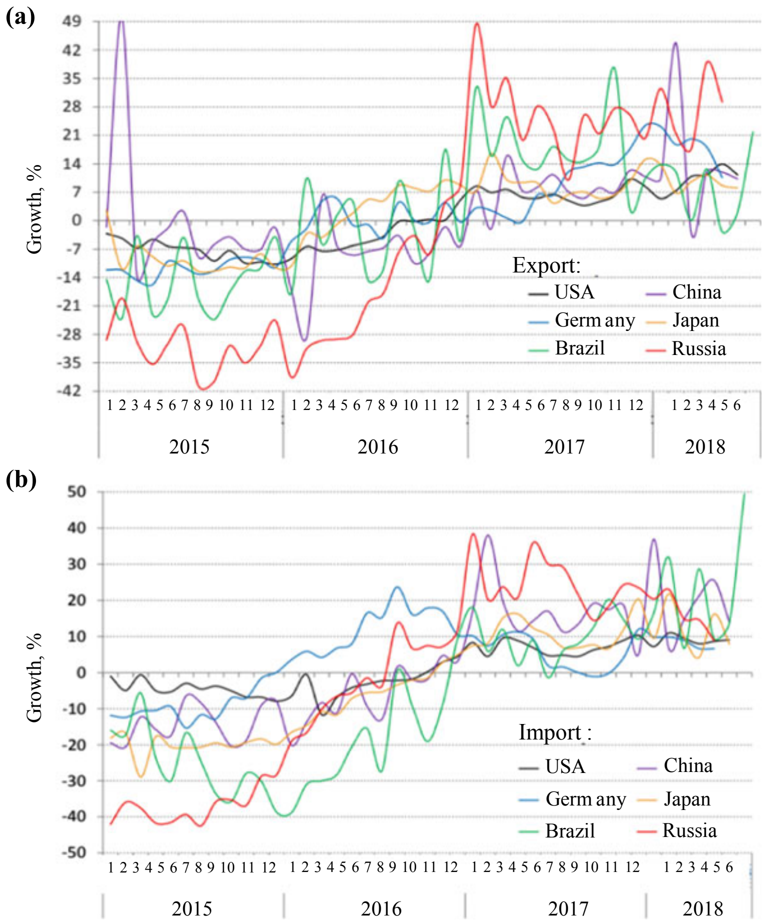


Fig. 1 Monthly dynamics of exports (**a**) and imports (**b**) in the leading countries of the world in current prices in annual terms, 2014–2018

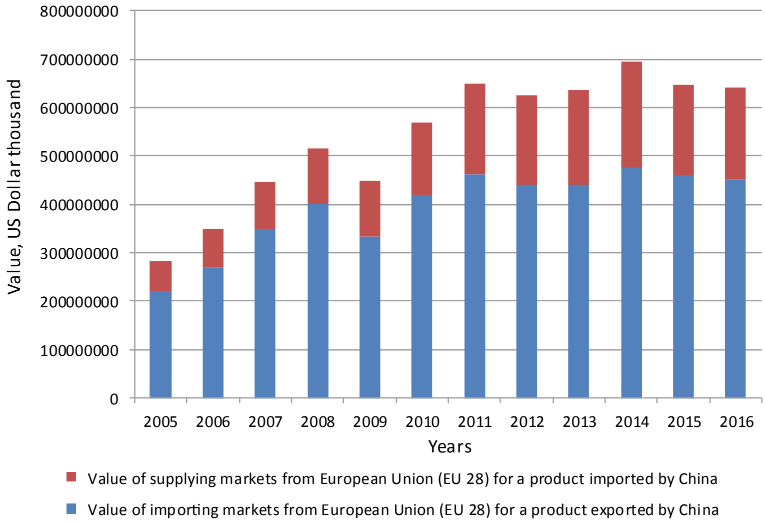


Fig. 2 The dynamics of foreign trade between the European Union and China

countries in the framework of specific transport and economic projects, the Silk Road Economic Belt and the 21st Century Marine Silk Road [3]. The fastest expansion pace of trade and economic ties is observed between the PRC and European countries. EU imports in 2016 amounted to 5218.6 billion US dollars. This amounts to almost 1/3 of the total volume of the global import market. At the same time, China's export to the EU countries has doubled since 2005 and amounts to 452.891 billion US dollars or about 8.7% of the total volume of the European Union import market in 2016 [4] (Fig. 2). Improving the welfare of China population, the active country urbanization makes the Chinese import market more attractive for the sale of products from the European Union [5].

The growth in production and consumption volumes negatively affects the environment—it leads to an increase in carbon dioxide emissions and waste generation. According to the World Resources Institute, only 20 countries managed to reduce the level of greenhouse gas emissions while increasing GDP [6]. This is not enough to achieve the strategic goals of the Paris Agreement to Combat Global Climate Change [7]—to keep the increase in global average temperature by the end of the XXI century within 2 °C.

The relevance of the environmental pollution problem is evidenced by indicators of the environmental capital overuse [8] in the global economy, the facts of uneven use by different countries of renewable energy sources [9], and also such an effective tool as state funding for solving environmental problems.

The main regional differences in climate protection and performance within the 56 evaluated countries and the EU can be proved by the Climate Change Performance Index (CCPI) 2018 results [9]. No country demonstrated well enough to reach the rating "very good", though growth rates in CO_2 emissions decreased a lot (Fig. 3).

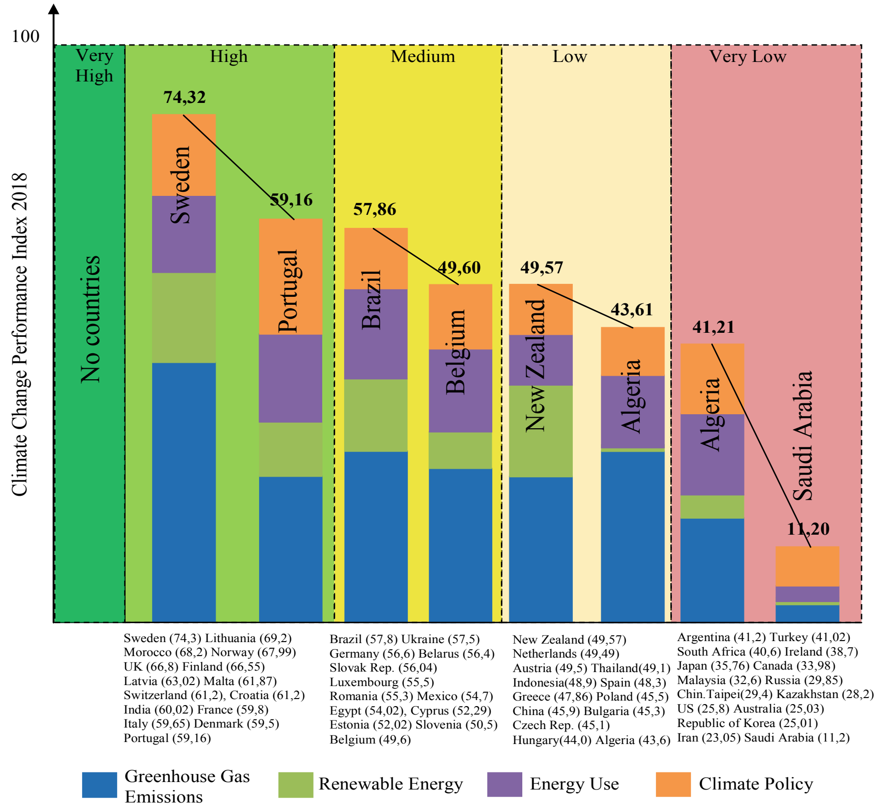


Fig. 3 World energy and natural resource use indicators

The increase in freight traffic in the global transport system contributes to the strengthening of state requirements for environmental aspects of transport and logistics activities. Such requirements become especially relevant for countries through territory of which the routes of international transport corridors pass or are planned [5]. The task of ensuring compliance with environmental requirements is most acute for world leaders in terms of carbon dioxide emissions—China, the USA, India and Russia [5, 10].

The solution to the problems of compliance with environmental requirements for transport is complicated by the presence of specific organizational and technological problems in the global transport system. The main problems in the interaction of the national transport systems that make up the international transport corridors are [5]: insufficient development level of the transport and logistics infrastructure and the lack of its transmission capacity; the use of various technologies for the delivery of goods and methods for organizing the interaction of various modes of transport; poor integration of transport systems of individual countries into the global transport system. In the conditions of uncertainty and dynamism of the external environment, the influence of many economic, social and environmental factors on the processes of promoting cargo flows, the presence of the above problems does not allow for effective mutually beneficial cooperation between countries. Beside these problems lead to an increase in investment and operating costs for the formation and development of transport corridors and transport facilities logistics infrastructure, strengthening the negative impact on the environment, and, as a result, does not ensure the goal achievement of sustainable development concept [11].

The sustainable development concept is based on the idea of achieving a reasonable balance between environmental, economic, social, cultural development and people's needs [11, 12]. The economic component of sustainable development is focused on the effective use of limited resources, saving energy, the use of environmental and material-saving technologies. The socio-cultural component implies maintaining the sustainability of cultural and social systems, an equitable distribution of benefits. The environmental component is focused on maintaining the integrity of natural systems for present and future generations.

Transport plays an important role in ensuring sustainable development, since, on the one hand, it is the most important tool for solving social, economic, and technological problems, and on the other, its functioning has a diverse negative impact on the environment and is an object of increased danger for the life and health of people [13, 14]. In addition, the transport system is the most energy-intensive and least environmentally friendly element of the supply chain. According to The International Energy Agency (IEA) [15], between 1990 and 2011, energy consumption in transport in the world increased by almost 55% to 102 exajoules (EJ), and transport became the fastest growing end-use sector. In 2001, transport accounted for 27% of global final energy consumption. The increase in associated CO_2 emissions generally matched this increase in energy consumption and reached 6.8 billion tons of carbon dioxide (billion tons of CO_2).

The negative impact of international transport corridors and supply chains on the environment is expressed in [13, 16] (Fig. 4):

- consumption of natural resources (energy, water, atmospheric and lithosphere resources);
- environmental pollution with harmful substances (gaseous, liquid and solid);
- energy and visual environmental pollution (noise, vibration, electromagnetic fields, heat emissions, light pollution);
- alienation and land degradation;
- injuries and deaths of people, animals, causing harm to health;
- causing material damage as a result of traffic accidents, accidents, and traffic accidents.

On the other hand, there is a gradual change in the attitude of the business, including transport, towards the idea of sustainable development and environmental problems, in particular. The main reasons determining such changes are [13, 17, 18]:

- state regulation and control of compliance with environmental and social laws by using not only restrictive (fines), but also incentive measures (tax benefits);

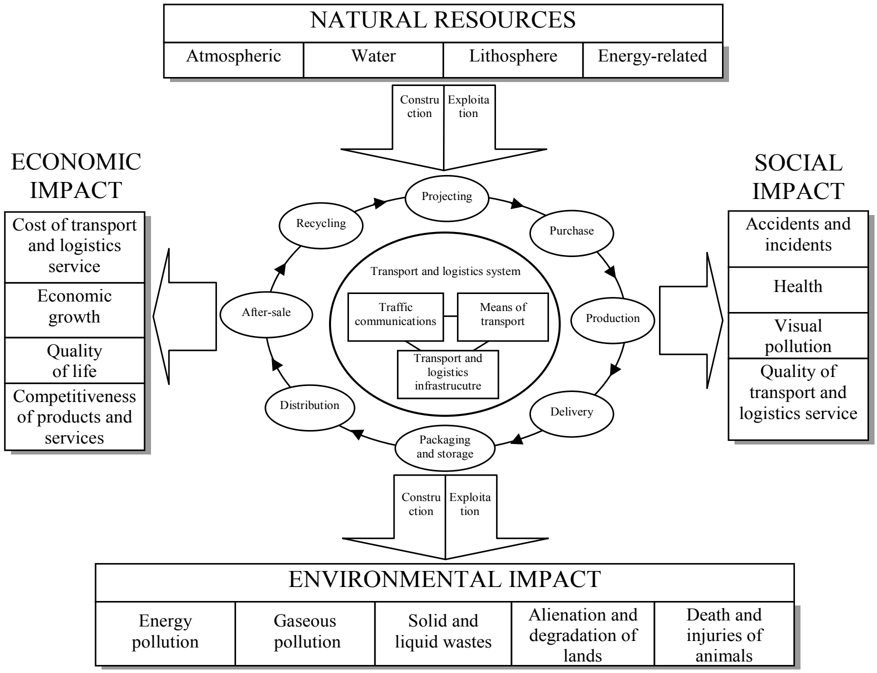


Fig. 4 The environmental impact of the transport and logistics system

- increasing requirements (demand) for the quality of services and products. Organizations that produce technologically advanced, high-quality and environmentally friendly products and services, increase the image of their brand and improve the reputation of their organization in the eyes of consumers;
- improving the reputation created by the public, own employees, consumers, shareholders, other companies (investment, insurance, banking), in turn, helps to increase the capitalization of the company, improve its financial performance in the long-term, as a rule, perspective;
- compliance with the requirements of supply chain partners, enhancing interaction with suppliers and customers, as well as shaping and developing social corporate responsibility;
- reduction of environmental and social risks. Socially and eco-friendly companies usually have lower insurance costs due to the fact that the size of insurance premiums is associated with decreasing environmental risks of enterprises;
- cost reduction and increased profits achieved through the use of modern environmentally friendly and at the same time cost-effective technologies;
- achieving a competitive advantage as a result of positioning products and services as environmentally friendly, which allows attracting profitable partners and conquering new markets.

The grouping of the considered reasons on the aspects of sustainable development allows us to understand the relationship between the features of the functioning of transport in the supply chain and the sustainable development concept [13]:

The environmental aspect. Assessment and consideration of environmental factors, as well as resource constraints, is necessary in the design and investment analysis, with strategic planning for the development of territories, justification of priority directions for the development of transport [19]. Studies [20] suggest dividing environmental factors into two groups: factors that negatively affect the environment during the construction of transport infrastructure, and factors that appear directly during the operation of transport systems. Insufficient consideration of environmental factors in the activities of transport and logistics companies leads to excessive consumption of natural resources; environmental pollution by harmful substances, energy and visual pollution; alienation and land degradation; reduction of biodiversity on earth, the emergence of environmental pathologies.

The social aspect. The consideration and assessment of social factors in the design and operation of transport and logistics systems is aimed at improving living standards as a result of mainly ensuring transport security, increasing accessibility and improving the quality of transport services to the population, protecting health, ensuring social welfare, and developing environmental competence of citizens and the development of a society's "environmental etiquette" in relation to transportation. The solution to the last two of these tasks is based on the formation of a people's systematic view of the human environment and understanding the impact of human activity on nature.

The economic aspect. The economic features of sustainable development of transport and logistics systems consist in harmonizing the sustainable development goals with the goals of transport functioning in supply chains—making a profit, economic growth, and increasing competitiveness. The main hypothesis of this coordination is that the implementation of logistic methods, concepts and functions fundamentally allows you to reduce the cost of resources and minimize costs, which potentially helps to reduce the harmful effects on the environment.

The modern logistic approach to the consideration of transport systems and the implementation of logistic methods and solutions [21–23] makes it possible to ensure that transport corresponds to all aspects of sustainable development at the same time. This is achieved mainly as a result of rational use of resources and improving the quality of transport services. A comprehensive systematization of factors influencing the sustainable development of the supply chain, presented in the form of a logistic system, was made in [13] (Fig. 5) on the basis of the logistic approach.

Presented in Fig. 5 system of factors for the sustainable development of supply chains is used by the authors as the basis for the development of indicators for assessing logistics flows in supply chains, the systematization of green technologies in transport, as well as methods for selecting tools for managing the parameters of logistics flows in green supply chains.

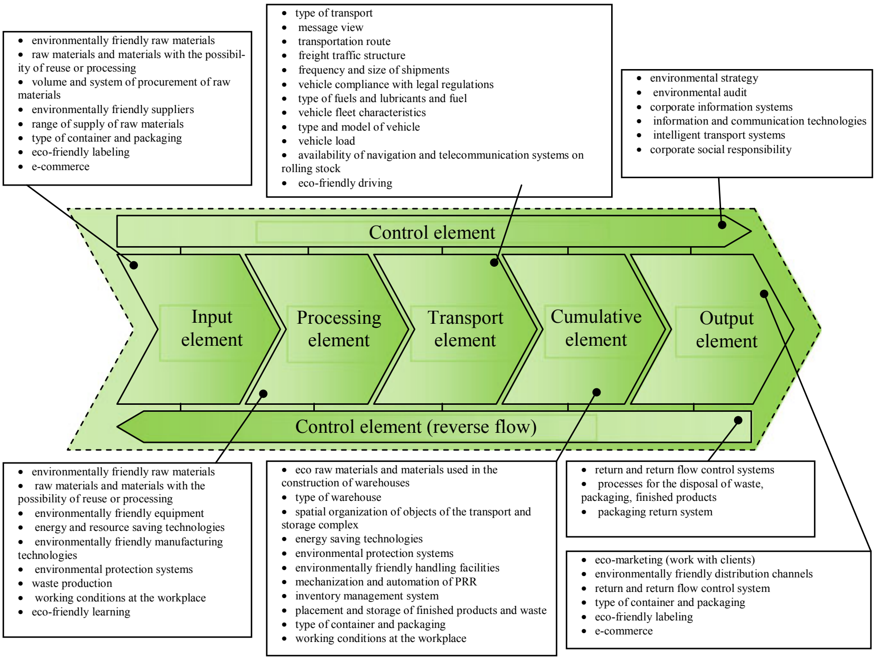


Fig. 5 Factors scheme of the transport and logistics system sustainable development

2 Research Review of Sustainable Development in Transport Systems and Supply Chains

To date, the key guideline for environmental policymaking for most countries is the "Sustainable Development Goals" (SDGs)—a universal set of 17 goals and 169 goals that are included in the global strategic program "Transforming our world: Agenda day in the field of sustainable development for the period until 2030" [12]. The achievement of the SDGs is based on the principle's implementation of sustainable development and largely depends on the activities of international organizations, the coordination of national, regional and international development programs, as well as ongoing activities in the field of ecology, environmental protection and in the economic sphere.

The majority of existing sustainable development models is based on achieving a reasonable balance between environmental, economic, cultural and social development and people's needs. However, the complexity of implementing this approach, as shown by the analysis of well-known models of sustainable development [5, 24], is associated with the following circumstances:

- static and insufficient emphasis on the dynamics of the development process;
- fragmented relations between aspects of sustainable development (ecology, economy and society);

- implementation complexity associated with a variety of constraints and the inconsistency of sustainable development goals.

With regard to transport systems, sustainable development means that meeting transport needs should not contradict the priorities of protecting the environment and human health, and will not lead to irreversible natural changes and the depletion of irreplaceable resources [21]. The work [25] notes the growing interest in the Concepts of Sustainability, Livability, Sustainable Development and Sustainable Transport. Despite the difference in approaches and definitions of the listed concepts, most experts talk about the balance of economic, environmental and social aspects of sustainability.

A logistic approach to solving environmental problems and implementing the principles of sustainable development began to be applied in the 1980s of the XX century [16, 26]. In work [27], four stages of priority research on the problems of the interaction of logistics and the environment are distinguished: economic rationalization of environmental factors in production (until 1990); development of Reverse Logistics (1990–2000); Green Logistics on Enterprise Level (2000–2010); Green Supply Chain Management (from 2010 to the present).

Many scientists note that logistics has significant potential for environmental monitoring of transport systems, product recycling processes, control and minimization of environmental pollution, energy and resource conservation processes [16]. At the same time, a number of scientists [28–30] note the contradiction between the classical logistic approach aimed at maximizing profits, ensuring economic growth and green logistics, which is associated with a decrease in the negative impact on the environment.

In [21, 31] it is shown that the concept implementation of sustainable development and green logistics is currently carried out on the basis of two approaches—state and market. The first is based on public administration and the observance by companies of mandatory requirements and restrictions, both forcibly and on the basis of incentive measures. The market approach is based on obtaining economic benefits, competitive advantages, increasing the image and public popularity of companies using green technologies.

In features studies of managing green supply chains, six main subject areas are distinguished [32, 33]:

- Policy—issues of business ethics and corporate social responsibility, environmental audits, as well as solving problems on environmental issues, compliance with the requirements of the law and the state in the field of ecology;
- Synthesis—literature reviews, studies, and training aids on managing green supply chains at all stages of the goods delivery from purchase to sale;
- Purchasing—environmental problems associated with the relationship between suppliers and customers, environmental solutions, certification and issues of compliance with environmental quality standards;
- Manufacturing—problems of design and construction, development and manufacture of ecologic products in order to reduce harmful emissions and wastes;

- Green logistics—environmental issues related to the sustainable transportation, handling and storage of hazardous materials, inventory management, warehousing, selection of locations for transport and logistics infrastructure, the preservation and use of containers and packaging, aimed to reduce CO_2 emissions;
- Reverse logistics—increasing the efficiency of logistics in the separation of return flows (material flows moving from consumers to the primary sources of these flows) into streams that are subject to secondary processing and utilized streams (waste).

The works [34, 35] give the analysis of existing and promising solutions for the integrated implementation of the state and market approaches to reducing the environmental impact of transport systems, and also the following grouping of these solutions was proposed:

- economic decisions are aimed at increasing the transportation cost, which forces companies, for example, to use cheaper and more environmentally friendly modes of transport, to optimize the workload of rolling stock;
- legal decisions are normative restrictions developed in advance and approved in the established manner. They can be used, for example, to accelerate the technological development of transport systems by gradually tightening the standards and requirements for vehicles, the level of harmful emissions into the environment;
- information and analytical solutions, for example, research, training, dissemination of best practices, benchmarking, consulting, the use of carbon calculators and environmental labeling;
- decisions in the field of social policy are focused on the development of a transport infrastructure that meets environmental requirements, the introduction of urban intelligent transport systems, the rational organization of passenger transportation, etc.

A review of existing and promising green technologies in transport and logistics [34, 36–40] showed a variety of approaches and views on the content of green logistics methods and instruments, which is the reason for the lack of systematic implementation. To date, various types of environmental programs and projects are actively implemented in logistics and transport companies around the world with the support of public and state institutions, the feasibility and effectiveness of green technologies use in practice have been substantiated [41]. At the same time, analysis of research results [16, 33] on the integration of the environmental factor into the practice of logistics management shows that research is still fragmented, in most cases affecting certain areas of logistics.

Approaches and methods for managing green supply chains vary in developed and developing countries [42]. The complex of Vancouver principles of sustainable transport [43], which is based on the idea of taking into account the environmental, social and economic conditions of different countries and regions within countries, had a strong influence on the sustainable development of transport systems.

In [44], eight sustainable development principles of transport systems are presented, which contribute to improving the quality of life and ensure economic viability while observing the requirements of the environment. The authors of [39] classify environmental principles applicable to supply chains in the following areas: product design, packaging, collection and transportation, waste processing and disposal, creation of an eco-business environment, storage, management questions (in the field of marketing and information technology).

The five principles underlying The GHG Protocol Corporate Accounting and Reporting Standard (relevance, completeness, consistency, accuracy and transparency) were used in paper [45] to formulate six principles for reducing carbon emissions from logistics activities. The authors of [36] examine the guidelines for environmental design (engineering) for supply chain sustainability in relation to product life cycle strategies.

The results of the scientific literature analysis presented in [26, 46], allowed to identify 151 logistic principles mentioned by various scientists. We have established that most of the well-known logistic principles implemented in practice ensure the achievement of management goals, assessed according to economic criteria, but poorly take into account the environmental aspects of logistics activities. This does not allow implementing the sustainable development concept in the management of green supply chains.

The complexity of managing green supply chains lies in the insufficiently investigated relationships between indicators and parameters of logistics flows. The scientific literature analysis [47] showed that there is no accepted universal system of parameters and indicators for logistic flows.

The main meters of material [48] and transport [49] flows are considered to be the transport mass, transport route and transport time. As additional parameters characterizing the flow, use [50–52]: initial, intermediate and final points; geometry (trajectory) of the flow; length (measure of the trajectory); speed and time of movement; intensity. In [53], in addition to the volume of traffic and points of origin and redemption of traffic flows, it is proposed to describe the logistic flows as its composition, quality and cost. The study [54] proposes to separate the parameters of logistic flows into three groups, each of which describes both a separate logistic flow and a combination of homogeneous and heterogeneous flows.

In [55], the parameters of logistic flows in supply chains are grouped into four groups: quantity, quality, costs and time. The authors of [22] suggest that the parameters of logistic flows be divided into two groups: a group of physical parameters that reflect the spatiotemporal properties of flows and a group of statistical parameters that characterize patterns of change in physical parameters. The study [56] established patterns of interaction between the flow and structural elements of the transport system. It is proposed that flow estimation be performed taking into account two parameters: average flow size and disorganization of flow. In [57], a characteristic of the parameters of material flow (the flow of goods and vehicles) in the logistics system is presented. The author [58] established the relationship between the quantitative parameters of flows and stocks in logistics. In [59, 60], an assessment of logistic flows by two components is proposed: vector (flow direction) and scalar (volume of resources). In [59], in relation to this approach, a complex of thirty-five indicators for assessing the total costs (financial flows) arising from the formation of innovation flows in the logistics system is proposed. In [61], a “metric” of information flow in logistics was proposed, and in [62] a relationship was established between the parameters of material, information, labor and financial flows in the logistics system.

The drawback of the majority of existing approaches to the assessment of all logistic flows is the consistency lack in the parameters and flow indicators consideration. In logistics practice, the assessment of material flows is carried out mainly by such parameters as mass, speed (time), and the route of advancement. This is due to the fact that these flow parameters are controllable. The traditional mechanism for managing logistics flows is based on decision-making on the results of comparing the actual values of these controlled parameters with the calculated (planned) ones. However, the calculated values of the controlled parameters are the result of stream optimization exclusively according to logistic, mainly economic criteria, known as the “seven right of logistics” [63] and do not take into account the environmental and social aspects of modern logistics activities.

At present, when solving complex multifactorial and multicriteria problems of forming and managing green supply chains, multicriteria decision-making approaches (MCDM) are widely used, which can be used to quantify the trade-offs between economic, social, and environmental criteria of sustainable supply chain development. In the scientific literature, MCDMs are divided into two categories [64]: a small and finite set of solutions called multi-factor decision making (MADM) and a large and infinite set of alternatives called multi-purpose decision making (MODM) or multi-purpose programming (MOP) a small and finite set of solutions, called Multi-Attribute Decision Making (MADM), and a large and infinite set of alternatives, referred to as Multi-Objective Decision Making (MODM) or Multi-Objective Programming (MOP). MADM approaches are aimed at determining the best option based on the known attributes of a limited number of alternatives, while MODM approaches are aimed at finding the best solution that satisfies the wishes of the decision maker.

The variety of parameters, properties and characteristics of logistics flows in supply chains makes it necessary to combine MCDM with various fuzzy approaches and methods. The use of methods of the fuzzy sets theory and methods of making managerial decisions is justified by the need to take into account many factors determined by the specifics of the functioning of transport systems and supply chains, as well as the variety of flow parameters circulating within the framework of the logistics system (supply chains). Unlike traditional mathematical methods that require precise and unambiguous formulations of laws, fuzzy set theory methods allow, based on both accurate quantitative indicators of the functioning of transport systems and approximate qualitative estimates, to generalize data on various factors that have different effects on the sustainability of supply chain development.

The analysis shows that in the practice of managing green supply chains, the authors use various fuzzy approaches and methods, in particular, fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) [65–67], fuzzy Importance and Performance Analysis (FIPA) [68], fuzzy Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [69, 70], fuzzy Analytic Network Process (ANP) and fuzzy Technique for Order Preference by Similarity Ideal Solution (TOPSIS) [66, 71, 72], analytic hierarchy process (AHP) AHP-TOPSIS and fuzzy Grey Relational Analysis (GRA) [73–75], interpretive structural modelling (ISM) [76–78], fuzzy game theory [79, 80] and others.

Applications of fuzzy goal programming has been studied in the supply chain when evaluating and selecting suppliers [81–83], designing a supply chain network [84, 85], supply chain planning [86, 87], evaluations job safety [88, 89] and urban transport systems [90].

The studies [91] proved the effectiveness of using mixed methods for theory in managing green supply chains, allowing taking into account the dynamic nature of green supply chains.

In studies [92], using the fuzzy Multi Criteria Decision Making (MCDM) approach, analyzing the drivers of green manufacturing was performed. In [93], a fuzzy model and methodology for a comprehensive assessment of eco-innovation was proposed. The following work [94] presented a multi-purpose mathematical model for improving economic and environmental performance of a supply chain that works under fuzzy environment and can handle multi-objectives.

An optimization model based on a fuzzy game theory for three players (government, manufacturers and customers) was proposed in [79] with the goal of choosing an optimization model of three-player payoff based on fuzzy game theory in green supply chain). The authors of [80] propose three models of green supply chain management with government interventions under fuzzy uncertainties of both manufacturing cost and consumer demand.

The paper [73] considers group decision making using fuzzy and gray set theories helped to give better results in green supplier selection. The fuzzy green supplier selection model proposed in [95] is based on the 4R principle (recycle, reduce, reuse and replace) and six sigma quality indices. The authors of [96] propose a comprehensive assessment of the cost structure in green supply chains using the process of the fuzzy analytical hierarchy of the entropy weight fuzzy analytic hierarchy process.

The authors of [97] analyzed the use of fuzzy demand to GSCM, proposed two nonlinear integer programming models, a crisp model and a fuzzy model. A genetic algorithm (GA) and hybrid genetic algorithm-pattern search (HGAS) are developed to solve the models.

The works [98, 99] presented a fuzzy programming model for designing a forward network supply chain aiming at minimizing the environment emission and total cost.

The disadvantage of most existing methods and models is the lack of comprehensiveness and systematic assessment of all types of logistics flows to take into account the relationship between indicators and flow parameters to achieve the goals of the concept of sustainable development. Thus, a review of research in the sustainable development field of transport systems and supply chains allows us to draw the following conclusions:

- the conceptual and terminological apparatus of green logics and management of green supply chains has been formed, approaches and principles of sustainable development have been formulated, there are systems of indicators for assessing this activity; a regulatory framework has been created for the practical implementation of the concept of sustainable development, which includes a set of regulatory legal acts of international and national legislation;

- there is no universal system of logistics principles, and most of the well-known and implemented logistics principles are aimed at improving management efficiency and achieving the economic goals of supply chain functioning;
- insufficient systematic implementation of the methods and instruments of green logistics in practice often leads to a decrease in the effectiveness of each of these methods and instruments separately, and does not contribute to the emergence of a green synergistic effect in supply chains;
- generally accepted logistics management criteria poorly take into account environmental and social aspects, which reduces the efficiency of managing logistics flows in accordance with the goals of the concept of sustainable development.

3 Comparative Analysis of Commodity Flows and the Benefits of Green Logistics

The volume analysis of trade flows in the global economic system demonstrates their following dynamics: a smooth increase until the end of the 1990s; sharp growth since the beginning of the 2000s; sharp decline after the 2008 economic crisis. In recent years, there has been a gradual restoration of traffic volumes in the global transport system. World export of commercial services and World merchandise exports increased from 1995 to 2014, respectively, from 1.179 to 4.872 and from 5.168 to $19 billion [100]. The global logistics market is anticipated to register a CAGR of 3.48% from 2016 to 2022 to attain a market size of around $12,256 billion by 2022 [101].

The commodity structure of freight flows in the global transport system in 2017 is presented in Figs. 6 and 7. The largest volume of transportation is accounted for by capital, intermediate and consumer goods, which in the structure of world exports and imports reach up to 45% of the total volume. In addition, in the structure of world trade, there is an increase in traffic between the EU countries and China [5, 102]. At a fast pace, there is an increase in the supply of various food products.

Such positive dynamics in the development of international trade and the organization of new transport links of international traffic contributes to an increase in requirements for existing transport corridors, makes it urgent to convert them into green supply chains [103], and to develop sustainable transport systems that can cater for increasing volumes of traffic internationally and nationally, as efficiently as possible, ensuring a reduction in the environmental load at all stages of the cargo delivery process. At the same time, the analysis of indicators of economic transport growth and development in a number of countries (the USA, the UK, Japan, and Germany) shows that indicators of freight activity stabilize or even decrease when a country reaches a high level of economic development [104]. This is mainly the

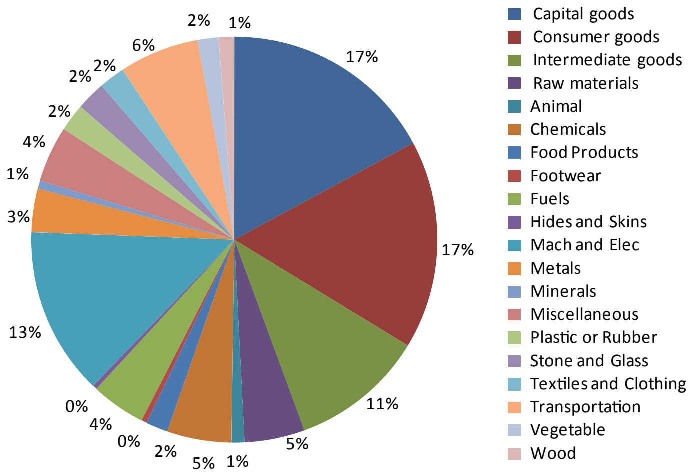


Fig. 6 World merchandise export by major product groups, 2017

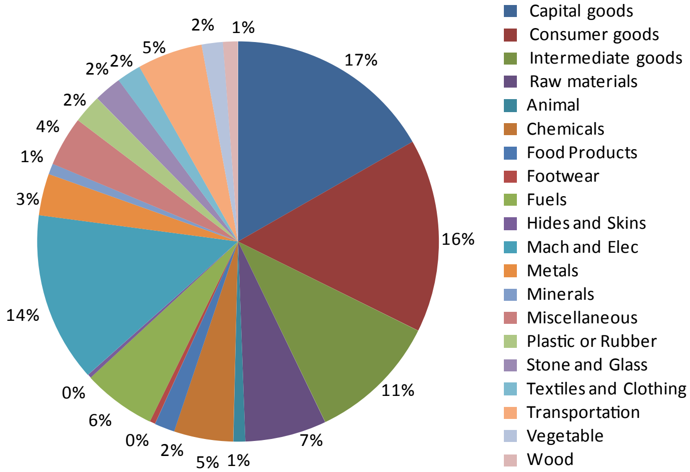


Fig. 7 World merchandise import by major product groups, 2017

result of adopting a low-carbon transport policy, structural changes in the economy and/or improving logistics management in transport and manufacturing.

The activities of logistics and transport companies, on the one hand, contribute to significant environmental pollution by harmful gaseous, liquid, and solid substances [13]. On the other hand, companies are increasingly using innovative methods and methods of “decarbonizing the economy” [105], implementing green strategies in business processes by considering green business practices in various functions of the business value chain [106]. According to Lise Kingo, Executive Director of the UN Global Compact, "Many companies are already starting to look through the Sustainable Development Goals—imagining how their operations, products and services can support the realities of our planet and better serve markets both today and in the future" [107].

The company on the way to sustainable development goes through three stages [105, 108]:

1. Development (formation) of a sustainable development strategy when senior managers consider climate change issues as strategic issues of their own business, and the measure development and adoption are compatible with their business interests.
2. Localization, which provides for the implementation of strategic plans for sustainable development by using green technologies by companies in practice, involving middle managers in the creation of new structures at the local level, involving all participants in the supply chain (from suppliers to consumers) in the implementation of eco-friendly-initiatives.
3. Normalization, which consists in reaching a compromise between business needs and sustainable initiatives. This stage is the most difficult, because the company faces a choice: to continue implementing sustainable development programs or return to familiar practice. The reasons for this choice may be, for example, financial difficulties, unjustified expectations from the implementation of programs, etc.

Researchers [17, 33] identify seven key benefits of green logistics and green supply chains:

1. Positive impact on financial performance. As a rule, the effectiveness of financial indicators is considered in the long term.
2. Sustainability of resources, i.e. efficient use of the organization's production resources.
3. Lower costs and increase efficiency. Effective resource management (including waste reduction, disposal and reuse) helps reduce operating costs, reduce fines, as well as the use of tax benefits and other economic instruments.
4. Product differentiation and competitive advantage. Positioning services and products as environmentally friendly allows attracting profitable customers (partners), strengthens the image of the company and its reputation on the market.
5. Regulation and risk reduction. The introduction of green technologies reduces the risk of being held accountable for violating environmental standards and using unethical business practices.
6. Improving the quality of services and products. Organizations that produce technologically advanced and environmentally friendly products increase the brand image and reputation of customers.
7. Involvement of the company, supply chain partners, employees, suppliers and customers in the development and implementation of long-term green solutions. This helps to strengthen relations with customers, forms and develops corporate citizenship and social corporate responsibility.

The best practices review for implementing green technologies in various business areas [109, 110] and in supply chain management in the countries of South [105, 111] and North [17, 112, 113] America, Western Europe [17, 37, 114–116], Eastern Europe [116, 117], Northern Europe [35], Southern Europe [115, 118], India [118–120], Asia [74, 121, 122], Australia [105], as well as in the work of logistics operators around the world [17, 109, 112, 121, 123, 124], showed a variety of approaches and views on the content of the methods and instruments of green logistics [33, 41].

In the practical activities of companies, such diversity leads to a decrease in the effectiveness of each of these methods and instruments separately, and does not contribute to the systematic reduction of harmful environmental impacts, provided that the supply chains are more economically efficient. As an example of insufficient systematic use of green logistics methods, Tables 1 and 2 [41] provide brief characteristics of large transport and logistics companies that use green technologies and the principles of the concept of sustainable development. The green technologies (solutions) used by companies were grouped according to the elements of the logistics system and the functions of these elements [22]. In distinguishing the logical elements and their functions, the approach proposed in [31, 40] was used.

In order to assess the prevalence of certain green technologies and green logistics methods, the authors analyzed the number of references in the scientific literature, as well as the number of green technologies implemented in practice. Figure 8 presents the results of the decomposition of the number of references and identified cases of the implementation of green technologies according to the elements of the logistics system and the functions of these elements. The detailed description of the structural and functional approach to the presentation of transport systems and supply chains in the form of logistics systems with the allocation of logistics functions and elements is presented in Sect. 4. In accordance with this approach, the following logistics elements are distinguished: input; output; processing; transport; cumulative. The selection of these elements is justified by the set of supporting logistic functions performed by them. A complete list of the supporting functions of the logistic elements is presented in Table 4 (Sect. 4).

Figure 8 uses the following notation for the columns of a chart:

- height of blue columns—the number of references in the scientific literature of green technologies with distributions by elements of the logistics system;
- the height of the green columns—the number of references in the scientific literature to green technologies with the distribution of the supporting functions of the elements of the logistics system;
- the number of brown columns—the number of identified green logistics methods that implement the corresponding function of the logistic element;
- height of brown columns—the number of references in the scientific literature to green logistics methods, with a distribution by function of the elements of the logistics system;
- the height of the yellow columns—the number of companies that implement green technologies in practice, with the distribution of the elements of the logistics system by function;

Table 1 Characteristics of transport and logistics companies implementing green programs (projects) [41]

No.	Name of company (country)	Main activity	Name of the implemented program (project)
1.	Schenker AG (Germany)	International logistics provider	"Climate Protection Program 2020"; "Eco Plus", "Eco Ocean Lane", "Eco Charter", "Eco Warehouse", "Eco Neutral"
2.	Green Cargo (Sweden)	Railway Logistics Operator	"Environmental Impact Calculation"
3.	DHL (Germany)	International logistics company	"Go-Green"
4.	FedEx (USA)	Freight company	"EarthSmart"
5.	Kuehne Nagel (Germany)	Leading global provider of logistics services	"Go Clean-Go Green","Global Transport Carbon Calculator", "Climate Neutral Services"
6.	UPS (USA)	International Supply Chain Management Company	"Eco Responsible Packaging"
7.	K Line Logistics (Japan)	International logistics company	"Drive Green Network"
8.	COSCO Group (China)	International container operator	"Wind Wing Ship", "Green Trip"
9.	Ekol (Turkey)	Transport and logistics operator	"Virtual Server"; Participation in the program "WWF Green Office"
10.	JSCo "Russian Railways" (Russia)	State Railway Company	The environmental strategy of Russian Railways for the period until 2017 and the future until 2030
11.	PJSC "TransContainer" (Russia)	Container operator	Separate projects
12.	UCL Holding (Russia)	International Transport Group	Separate projects

- the number of yellow columns—the number of green technologies implemented in practice that correspond to a certain method of green logistics and the function of the logistic element.

The results of the analysis allow us to conclude that at present no methodological base has been formed for the practical implementation of the sustainable development concept in relation to transport systems and supply chains. There is still a process of accumulation and selection of private solutions (technologies and methods) to reduce the harmful effects of transport on the environment. Research is needed to

Table 2 Systematization of green technologies used by transport and logistics companies [41]

Logistic system element	Logistics system function supported by green technology	Implemented green technologies (Company No., in accordance with Table 1)
Input element	Supply quality analysis	The use of environmentally friendly fuels and lubricants and fuels (1–4, 6–9, 12)
Processing element	Production and product quality management	Organization of a waste management system (10, 11, 12)
	Personnel management	Eco-friendly staff training (1, 9, 10)
	Improving technical and technological support	Designing energy-efficient rooms (3, 4, 5, 10); The use of environmentally acceptable engineering and technology in the production process (10); Alternative energy sources (1, 4, 6, 8, 9, 10, 11)
Cumulative element	Inventory level optimization	Reduction of stocks and consumption of materials and spare parts (8)
	Improvement of technical equipment and storage technology	Environmental design of warehouse complexes (1, 5); Use of energy and resource saving equipment (1, 4, 6, 7)
Output element	Selection and organization of product distribution channels	Application of technologies for managing reverse and return material flows (3, 5, 6, 9); Packing and packaging management (reverse logistics methods) (4, 5, 9)
	Service flow formation	Stimulating consumers to use green services (2, 3, 4, 5, 12); The use of eco-packaging and returnable packaging (3, 4); Weight and volume optimization of packaging material (4, 5)
Transport element	Selection of optimal transportation schemes	The use of intermodal technologies and multimodal transport (1, 2, 6, 9, 10); Optimization of driving routes according to the criterion of minimum harmful effects on the environment (1, 2, 3, 5, 8, 10); Analysis and optimization of emissions (2, 3, 4, 5)

(continued)

Table 2 (continued)

Logistic system element	Logistics system function supported by green technology	Implemented green technologies (Company No., in accordance with Table 1)
	The choice of a system for organizing the promotion of material flows	Formation of long trains (1); Consolidation of Supplies (6)
	Operational management of material flow parameters	Vehicle speed optimization (8)
	Improving the technical support of the transportation process	Use of environmentally friendly vehicles (1, 2, 3, 4, 6, 9); Use of energy-saving equipment (1, 2, 8, 10); Modernization of the fleet of vehicles, modification of transport equipment (1, 3, 4, 7, 8, 10, 12)
Control element	Logistic strategy development	The inclusion of environmental aspects in the company's strategy (1–12); Implementation of a transparency policy (1–12)
	Organization of interaction and coordination of the work of LS elements	Implementation of integrated environmental protection systems (10, 11)
	Coordination and regulation of LS elements	Electronic (paperless) workflow (1, 4, 8, 10); Use of intelligent transport systems (1, 7, 8); The use of modern information systems (6)
	Formation of a favorable socio-economic environment of LS	Dissemination of information on environmental achievements (1–12); Formation of corporate social responsibility in the field of sustainable development (1–12)

systematize the found effective solutions (green technologies, green methods) and to create a general theory of sustainable transport development. The author's version of such systematization is presented in [40, 125]. The proposed system of methods and instruments (technologies) of green logistics is based on the factors study of sustainable development of transport and logistics systems, as well as on the use of a structurally functional approach to the description of logistics and transport systems, involving the identification of the basic and supporting functions of the elements of these systems [22].

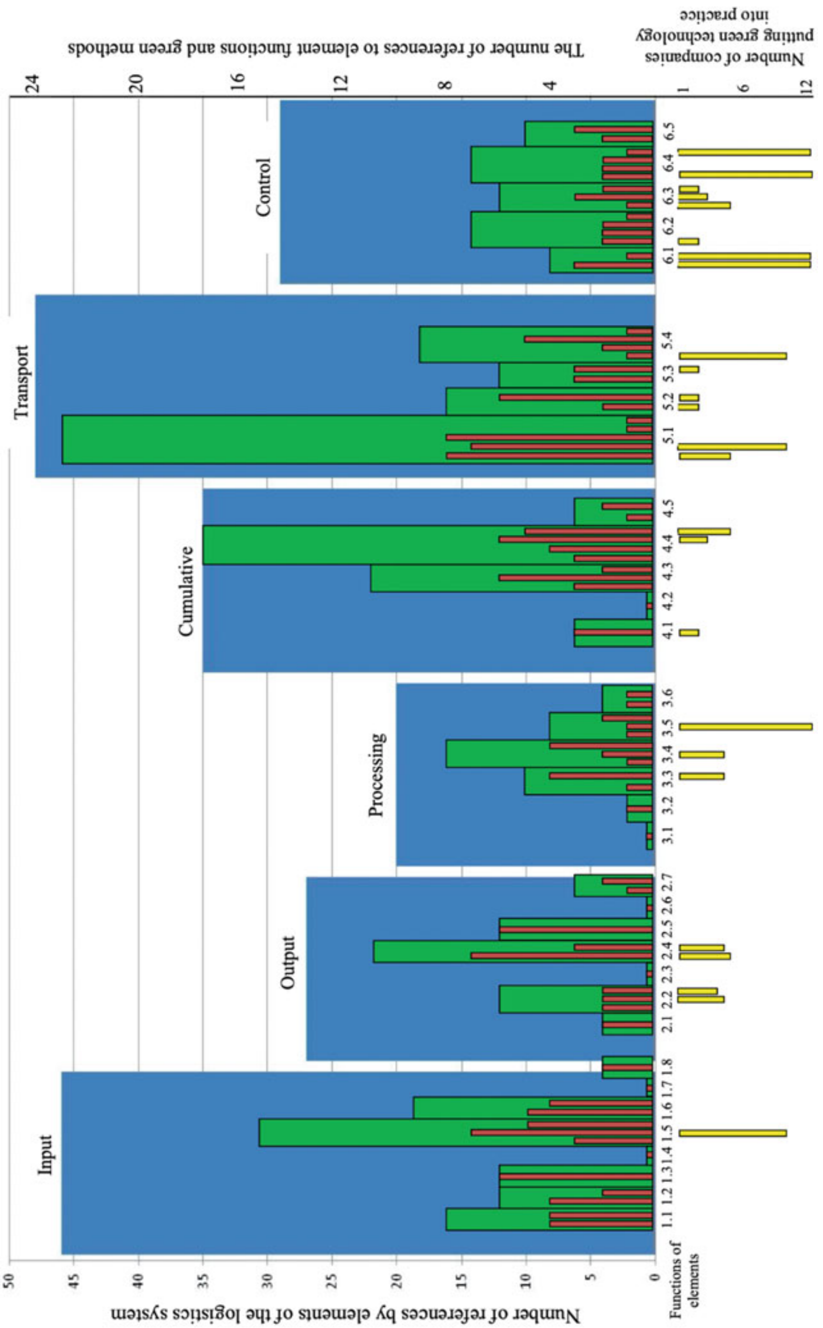


Fig. 8 The number of references and cases of using green technologies in logistics activities

4 The Concept of a Logistics Flow Management System in Green Supply Chains

The analysis of the goals, objectives, advantages and disadvantages of the implementation of a particular conceptual approach in logistics shows that the issues of reducing the negative impact on the environment and achieving sustainable development goals are indirect and, as a rule, are focused on compliance with current regulatory and legal restrictions and requirements in environmental areas to be performed by companies operating in the logistics services market. At the same time, many scientists note that logistics has a significant potential for solving environmental problems. Table 3 presents the qualitative assessment results of the environmental

Table 3 Qualitative assessment of the environmental potential of logistics concepts

Environmental impact	Concept[a]
Positive	
Selecting nearby suppliers of material resources	JIT, LP
Reduction of the transport component due to effective feedback on orders	RP, DDT, SCM
Choosing the optimal mode of transport and driving route	RP, SCM
Minimization of defects (defects) in the production process and, as a result, waste reduction	JIT, LP
Minimization of the level of stocks of material resources, work in progress, finished products, waste	RP, JIT, DDT, LP, SCM
Reduced need for storage space by reducing inventory levels	RP, JIT, DDT, LP, SCM
Reduced energy intensity and rational use of storage facilities, rational land use	JIT, LP
Formation of corporate social responsibility as a necessary condition and result of the implementation of logistic concepts and the creation of green supply chains	JIT, LP, SCM
Returnable material management (reverse logistics)	DDT, SCM
Negative	
The increase in the intensity of use of transport in the transition to production in small volumes with a high frequency of departure	RP, JIT, DDT, LP
An increase in the volume of loading and unloading operations due to a decrease in the size of consignments	RP, JIT, DDT, LP
Increased environmental load at the locations of transport corridors and nodes	RP, SCM
The use of buffer depots for storing stocks of raw materials, finished products and waste	RP, DDT
The increase in the number of failures in the system due to its large dimension and complexity	RP, DDT

[a]*Note* RP—Resource Planning, JIT—Just in Time, LP—Lean Production; DDT—Demand-Driven Techniques, SCM—Supply Chain Management

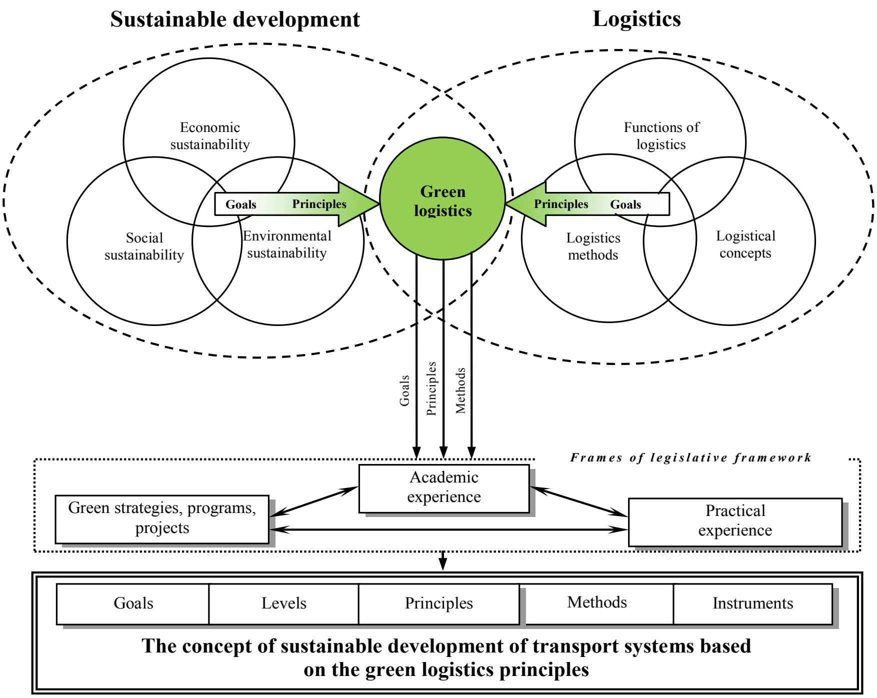


Fig. 9 The scheme of the proposed approach to achieving the sustainable development goals in the functioning of transport systems and supply chains

potential of existing logistics concepts. The number of references and cases of using green technologies in logistics activities are shown on Fig. 8.

The proposed concept of managing logistics flows in green supply chains (Fig. 9) is based on the idea of achieving a balance between the economic, environmental and social sustainability of the logistics system. The formation of such a system should be subject to the following conditions:

- consistency of logistic principles with the principles of the sustainable development concept;
- achieving and maintaining a balance between the economic, environmental and socio-cultural sustainability of the logistics system within the framework of the regulatory framework of international and national legislations;
- development of a system of methods and instruments for green logistics based on the best practices for the environmental programs and projects implementation in the activities of public and state institutions, business structures, research organizations and international associations.

The basis of the proposed concept is the following provisions:

1. *Achievement of sustainable development goals in the operation of transport systems and supply chains is achieved by bringing the goals, methods and principles of green logistics into line with the goals and objectives of the organization's business.*

The goals comparison of sustainable development and the goals of the functioning of transport systems show the presence of contradictions between them. If the transport system work is focused on achieving economic goals (improving the quality of services, making a profit, reducing costs), then the main goal of sustainable development is to achieve a balance between the economic, social and environmental needs of society. From the perspective of green logistics, it is necessary to look for the ways to coordinate the goals of sustainable development and logistics. The main hypothesis of such coordination is that the implementation of logistic methods, concepts and functions fundamentally reduces the cost of resources as a result of optimizing the parameters of logistic flows, which potentially helps to reduce the harmful effects on the environment. Effective, using logistics solutions, the use of resources allows us to improve the logistics processes, and as a result, realize the social and environmental needs of society. However, this requires the development of a system of functions, methods and concepts of logistics for the development of "synthetic" principles of green logistics, the observance of which will ensure the achievement of both logistics goals and sustainable development goals.

We systematized the functions, methods and concepts of logistics for the logistics system, which is considered as a model of transport systems. The authors of this work understand the logistic system as a complex, organizationally-completed economic system consisting of functionally separate elements interconnected in a single process of promoting material and related service flows, information and financial flows [26]. Each of the logistic elements performs certain functions of influencing the logistic flows (Table 4). The performance of these functions is necessary to achieve the goals of the logistics elements for the passage and processing of logistics flows (Fig. 10). In relation to logistics systems, it is necessary to distinguish the following functions, the implementation of which is carried out depending on the level of logistic tasks to be solved [22]:

- key functions are management functions of logistic elements and the logistics system as a whole;
- basic functions are generalized functions of influence on logistic flows. These include: supply (input flows into the system); production (qualitative changes in flows); transportation (flow promotion); storage (accumulation or deceleration of flows); sales, distribution (the withdrawal of flows from the system with the conversion of material flows and service flows into financial flows);
- supporting functions are specific functions of each element of the logistics system, which, in turn, are a set of specific operations (actions) to change the parameters of logistic flows. As a result of the implementation of logistics operations and supporting functions, the basic logistics functions of the logistics system are implemented.

Table 4 Basic and supporting logistic functions

Logistic element (basic function of the element)	Supporting logistic functions
1. Input (receipt of logistics flows in the logistics system)	1.1. Research of the supply marketplace
	1.2. Flows requirement identification
	1.3 Delivering methods identification
	1.4. Supplies costs analysis
	1.5. Supplies quality analysis
	1.6. Supply planning
	1.7. Supply controlling
	1.8. Parameters correction (quality) flows or flow requirements
2. Output (disposal of logistics flows from the logistics system)	2.1. Marketing researching of sales area and market requirement determining in LS products
	2.2. Market requirement deter-mining in LS products
	2.3. Pricing
	2.4. Flow services formation
	2.5. Deliveries and services traffic planning
	2.6. Supply and service control
	2.7. Parameters of supplies and services controlling
3. Processing (processing, changing the quality properties of logistics flows)	3.1. Production planning
	3.2. Coordination of work of structural units
	3.3. Production and product quality management
	3.4. Personnel management
	3.5. Improvement of technical and technological support
	3.6. Production cost management
4. Cumulative (deceleration, accumulation and storage of logistics flows, inventory management)	4.1. Inventory level optimization
	4.2. Control and regulation of stock levels
	4.3. Material flows management, their distribution in LS
	4.4. Improvement of technical equipment and storage technology
	4.5. Flow processing quality management
5. Transport (promotion, acceleration of logistics flows)	5.1. Selection of optimal transportation schemes

(continued)

Table 4 (continued)

Logistic element (basic function of the element)	Supporting logistic functions
	5.2. The choice of a system for organizing the promotion of material flows
	5.3. Operational management of material flow parameters
	5.4. Improving the technical support of the transportation process
6. Manager (coordination of the functioning of logistics elements for processing and promotion of material flows and service flows using information and financial flows)	6.1. Logistic strategy development
	6.2. Organization of interaction and coordination of the work of LS elements
	6.3. Coordination and regulation of LS elements
	6.4. Formation of a favorable socio-economic environment of LS
	6.5. Monitoring the sustainable functioning of LS

The determination of logistic functions based on a structurally functional approach makes it possible to systematize the logistic principle and methods for achieving sustainable development goals. In addition, this will allow you to group well-known green methods and instruments according to two main characteristics—belonging to a logistics element that implements one of the basic logistics functions, and according to the effect of the method on logistics flows based on the implementation of key management functions of logistics elements. This will exclude duplication of green methods at various stages of the logistic process; will allow identifying and using promising green methods and instruments.

2. *The formation and development of transport systems and supply chains is based on the system use of green logistics principles, which is a synthesis of the principles of sustainable development with logistic principles.*

The results of the analysis [26, 31, 33, 46] of the principles of sustainable development and logistics show that at present there is no universal system of logistics principles, and most of the well-known and implemented in practice logistics principles are aimed at achieving the economic goals of the functioning of logistics systems. Such an approach contradicts the concept of sustainable development, the purpose of which is to create a balance between the economic, socio-cultural and environmental needs of society. Table 5 presents the analysis results of the shortcomings of the known sustainable development principles and logistics principles.

For the effective implementation of the sustainable development concept of transport systems and supply chains, the authors have synthesized the existing principles of logistics and principles of sustainable development. The new synthesized system

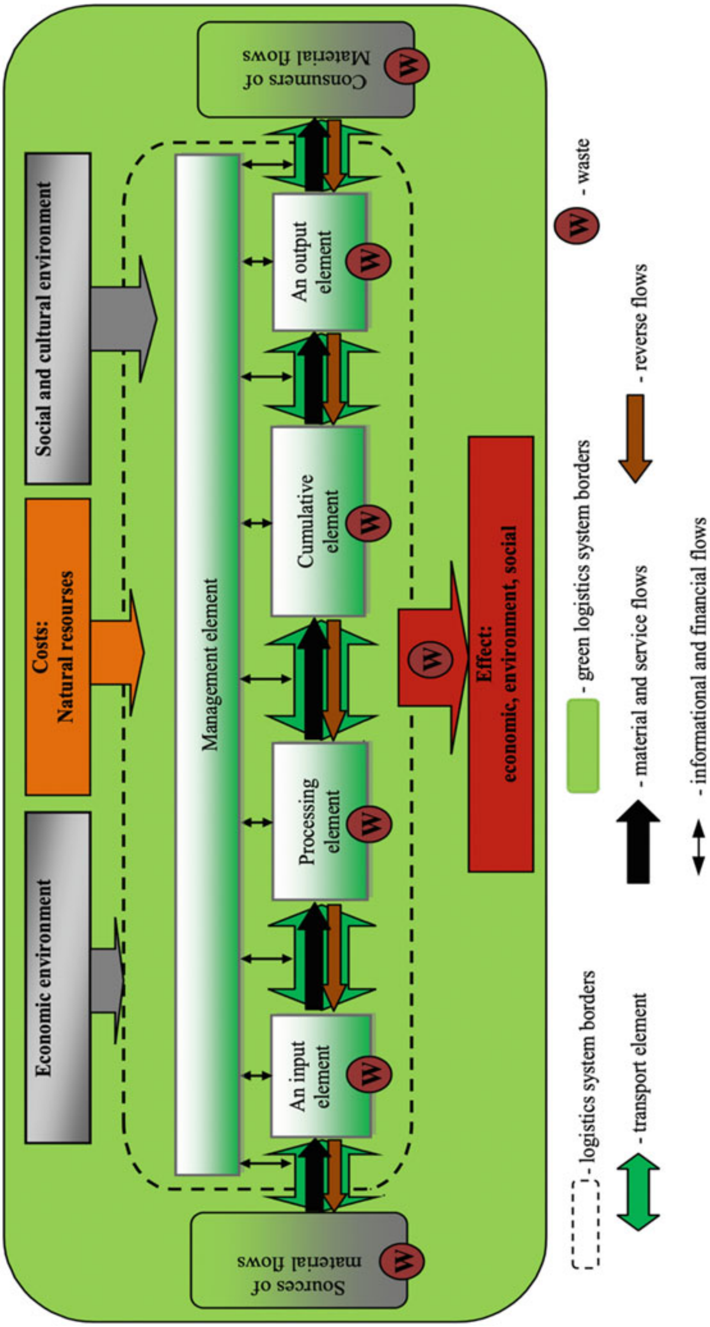


Fig. 10 Green logistic system diagram

Table 5 The results of the analysis of the shortcomings of the known principles of sustainable development and logistics principles

Principles of sustainable development	Logistics principles
1. **The lack of consistency** of generally accepted principles of sustainable development, expressed in the absence of their separation into environmental, economic and social aspects 2. **Differences in the interpretation** of the principles of sustainable development in the environmental legislation of different countries, leading to legal conflicts when transporting in international traffic 3. **The lack of concreteness** of the principles of sustainable development, which is the reason for the variety of methods and instruments for their implementation both at the state level and in the economic activities of companies	1. In scientific works there is a description of the set of logistic principles, but there is **no universal** accepted set (system) of logistic principles 2. A significant part of the logistics principles **is aimed at improving management efficiency** and achieving the economic goals of the functioning of the logistics system. This contradicts the principles of the concept of sustainable development, the purpose of which is to create a balance between the economic, socio-cultural and environmental needs of society 3. There is **no comprehensive and systematic** approach to the implementation of logistics principles in relation to the elements of the logistics system and their functions, logistics flows and levels of organization of logistics systems 4. **Numerous discrepancies in the applied terminology** and understanding of the essence of logistic principles, uneven use of these principles to regulate various types of logistics activities have been identified

of principles of green logistics is based on the idea of achieving a balance between the economic, environmental and socio-cultural sustainability of the logistics system.

Using the proposed system of principles in the practical activities of logistics and transport companies (in supply chain management) will allow us to efficiently develop and implement methods and instruments of green logistics, to ensure closer integration of supply chain elements, and as a result, to achieve the goals of the logistics system considering the requirements to reduce the harmful effects on the environment (Table 6).

3. *Achieving and maintaining a balance between the economic, environmental and social sustainability of the transport system is ensured by the implementation of the developed system of green logistics methods and instruments that affect the elements of the logistics system and logistics flows.*

The analysis [16, 33, 40] shows, currently found effective environmental solutions, including resource-saving and environmental-friendly solutions in the field of green logistics, are implemented haphazardly. Research is needed to develop a general theory of sustainable transport development and a system of methods and instruments for green logistics, in particular. The author's version of such a system is presented in [40, 125]. The proposed system of methods and instruments of green logistics is based on the study of factors of sustainable development of transport and logistics systems

Table 6 The system of green logistics principles [26]

Sustainability aspect	Principle name	The essence of the principle
Systematic sustainability	Principle of system	considering environmental, economic and socio-cultural aspects of the sustainable development of the logistics system and the relationships between them as a single system
	Adaptability principle	adaptation to the influence of external factors on the logistics system (to environmental changes) to maintain market sustainability and the effective use of advanced technologies
	Development principle	continuous and focused qualitative improvement of the structure and functions of the logistics system, methods, methods and instruments of green logistics
	Principle of self-organization	creation of conditions for the constant search and implementation of the found optimal environmental, economic and social solutions
Economic sustainability	Principle “polluter pays”	Compensation for environmental damage associated with the provision of logistics services at all stages of the promotion of material flow
	Justice principle	Proportional distribution between producers, sellers and carriers of the total benefits of meeting consumer demand
	The principle of efficiency and safety	Assessment of decisions in the field of the development of the logistics system in terms of economic efficiency, safety and the negative impact of the system on the environment

(continued)

Table 6 (continued)

Sustainability aspect	Principle name	The essence of the principle
	Optimality principle	The development of optimal solutions in the management of the logistics system is carried out on the basis of environmental costs as part of the total logistics costs
	The principle of non-waste and resource conservation	The maximum use of production waste, packaging and packaging as secondary raw materials or their environmentally friendly disposal, as well as the minimum use of raw materials and packaging not subject to reuse or safe disposal
Environmental sustainability	Principle of minimal impact	Reduction of negative environmental impact throughout the entire production, transportation, direct use and processing of material flows
	Principle of innovation	Introduction of innovative technologies in order to reduce the negative impact on the environment
	Rationality principle	Rational use of natural resources and all enterprise resources
	Sequence principle	The sequence of implementation of decisions on sustainable development of supply chains should correspond to the hierarchy of aspects of sustainable development: ecology -> economy -> society -> culture
	The principle "from particular to general"	The formation and development of a green logistics system is carried out sequentially—from a separate logistics element to the logistics chain or the logistics network as a whole

(continued)

Table 6 (continued)

Sustainability aspect	Principle name	The essence of the principle
Socio-cultural sustainability	Principle of responsibility	Increasing environmental responsibility of personnel and the formation of corporate environmental culture
	Transparency principle	Building relationships with customers and stakeholders based on interactivity, information and financial transparency
	Principle of reasonable consumption	The desire to reduce the transport needs of society and the state, not violating the rights and freedoms of movement and trade
	Competency principle	The formation and availability of competencies for all participants in the supply chain necessary for the sustainable development of these systems
	The principle of humanization	Compliance of logistic functions and operations with ergonomic, social, ethical requirements of staff

[13], as well as on the use of a structurally functional approach to the description of logistics and transport systems, involving the identification of the main (basic) and supporting functions of the elements of these systems [22].

The structural and functional approach used by the authors to systematize the well-known methods of green logistics is fundamentally different from the common way of distinguishing the functional areas of logistics: transport, marketing, production logistics, and supply and storage logistics. The disadvantage of this functional approach is the "linking" of logistics functions and operations to the infrastructure elements of the supply chain—warehouses, industrial enterprises, supply and sales departments, and transport. When using the functional approach to solving the problem of systematizing logistic methods, a situation arises when the same method of managing logistics flows is implemented in different functional areas of logistics. This is one of the main reasons for the inconsistent use of green logistics methods and instruments, when essentially the same methods and instruments are implemented on a different methodological basis, supported by various, often conflicting, and regulatory documents.

A typical example is the allocation in green logistics of a separate functional area—the so-called reverse logistics. In our opinion, such a separation is excessive, since the object of managing reverse logistics is also a material flow, consisting of production waste, packaging, secondary raw materials, but differing from the main material flow only in the direction of movement—it moves towards the main. In fact, the green methods of reverse flow control are implemented by the same logistic elements, the control object of which is the material flow.

The application of the structural-functional approach as the basis of the system of methods and instruments of green logistics allowed us to group the majority of well-known decisions in the field of ecology and resource conservation. Figure 11 presents the systems of methods of green logistics with the allocation of green logistics instruments in relation to the transport element of the logistics system.

The proposed method of systematizing the methods and instruments of green logistics is proposed to be used as a basis for assessing the effectiveness of the best practices in implementing environmental programs and projects in the activities of public and state institutions, business structures, research organizations and international associations. It is assumed that the result of such an assessment will be the expansion and improvement of this system of methods and instruments, which will ensure their coordinated practical application at various stages of the logistics process and at various levels of transport system and supply chain management.

5 Parameters and Indicators System of Logistic Flows in Green Supply Chains

The object of logistics research and management is a system of flows: material, information, financial and service flows. The traditional main goal of the logistic system is the promotion (processing) of flows with minimal costs, subject to timely satisfaction of consumer demand for high-quality goods and services. However, in the context of increasing anthropogenic impact on nature and the requirements of the world community to reduce the negative impact of transport on the environment, the "classic" goals of minimizing costs in the logistics system, without taking into account the environmental aspects of the functioning of logistics systems, are no longer relevant in modern world.

It is proposed that the goal of green logistics is to consider the quality maximization of the products and services provided by the logistics system, subject to the observance of economically justified costs of resources. The satisfaction of the social and environmental needs of society is also understood under the quality. For green supply chains, meeting these needs means increasing the timeliness and safety of transport, as well as reducing the flow of harmful environmental impacts. Achieving the goal of green logistics is limited by the consumed resources. The green technologies discussed in the third section make it possible the rational consumption of resources in green supply chains. Thus, a feature of managing logistics flows in green supply chains is the consideration of quality indicators of transport services (service flow), as well as the following material flows:

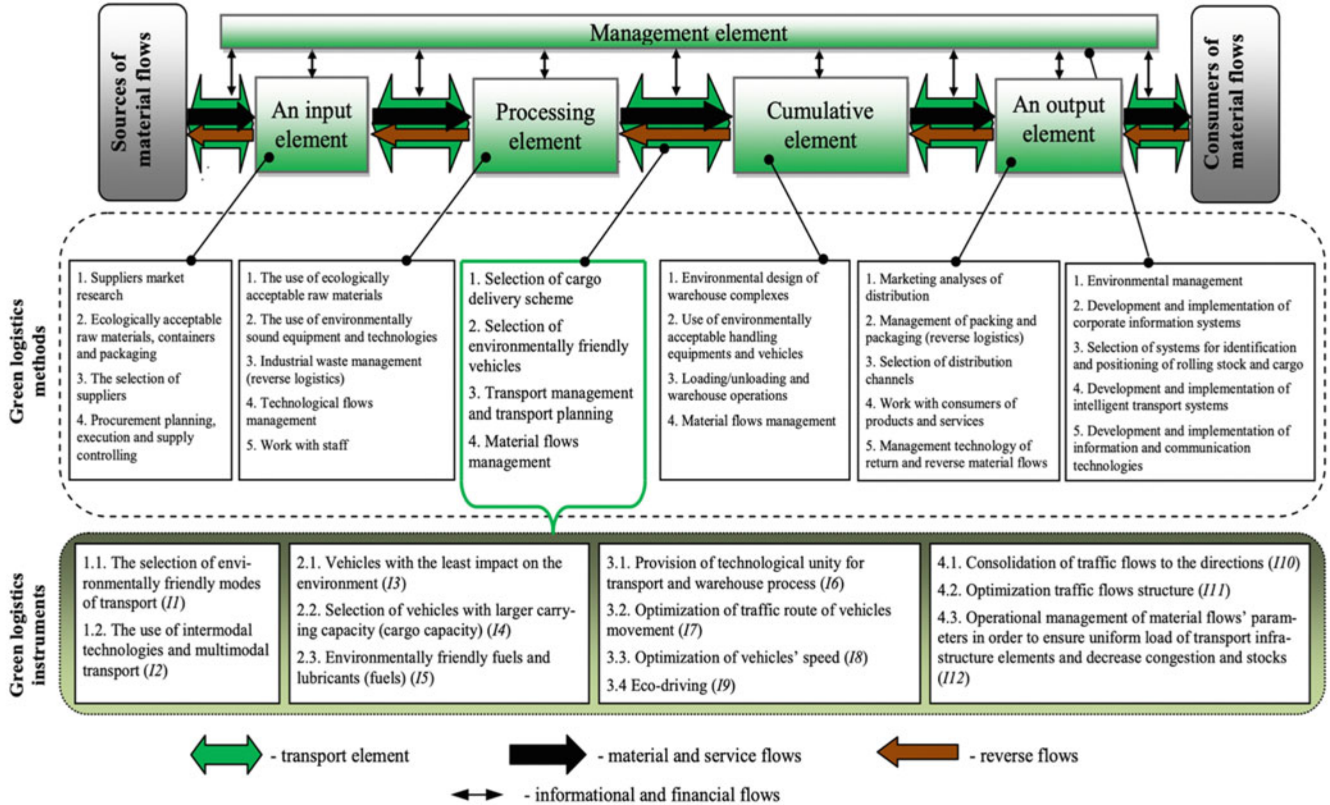


Fig. 11 Systematization scheme of green logistics methods and instruments (with the allocation of a system of green logistics instruments for the transport logistics element)

1. The flow of consumed primary and secondary energy resources. Without exception, all elements of the logistics system are consumers of non-renewable resources (fossil fuels) necessary for the implementation of logistics operations related to the generation, transformation, accumulation, storage, transportation and absorption of material and related information, financial and service flows. These resources directly (in the form of fuel for vehicles) or through energy conversion, transmission and distribution systems (power stations) in the form of electricity and heat are necessary to ensure the main and auxiliary technological processes.
2. The flow of polluting harmful substances. In the process of burning fuel, substances are released that have a negative effect on the biosphere. The main pollutants released into the atmosphere are sulfur dioxide (SO_2), nitric oxide (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter.
3. The flow of thermal energy into the surrounding space from the facilities of the logistics infrastructure, buildings and structures, vehicles. This effect contributes to the greenhouse effect and is one of the main causes of global warming.

The indicator "greenhouse gas emissions" is used in this work as the main parameter for assessing the flows of polluting pollutants and thermal energy. The calculation of this indicator is based on the guidelines of the IPCC (Intergovernmental Panel on Climate Change, IPCC) and the International Energy Agency (IEA) [126].

When developing a parameters and indicators system of logistic flows in green supply chains, the authors proceeded from the assumption that these flows, depending on the level of detail and at different levels of the control system, appear to be either discrete or continuous.

Discrete logistic flows are presented as a set of separate objects (elements or jets), for example, in the form of separate consignments or vehicles as part of a material flow or various logistic operations in a service flow. Such a presentation of logistics flows is necessary for the selection and implementation of logistics technologies at lower levels of management.

The presentation of logistic flows as continuous is used at the highest levels of management, for example, strategic, when the parameters of individual elements of the flow are not important, but it is necessary to operate with generalized (averaged) indicators, such as, for example, the intensity or average flow rate.

Given this approach, the authors propose using the following universal concepts on which the proposed parameters and indicators system of logistic flows in green supply chains is based (Fig. 12):

- logistic flow element—an elementary indivisible flow object that has certain properties;
- stream of the logistic flow—a part of the flow, which is a collection of elements that have the same (similar) properties;
- logistic flow—a set of jets perceived as a single whole and existing as a process at a certain time interval.

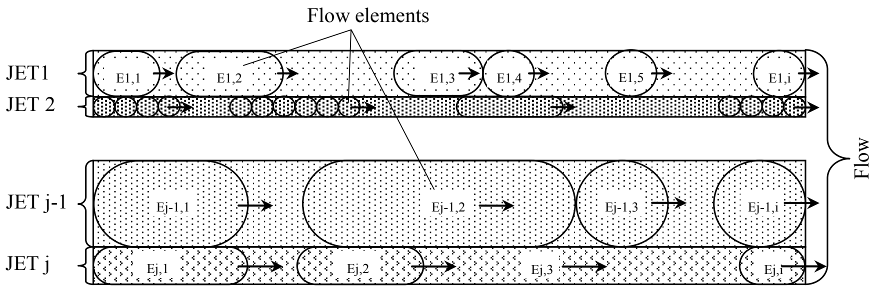


Fig. 12 Schematic diagram of the logistics flow structure

As an example, explaining Fig. 12, let us consider the movement of a material stream, consisting of the *j*th number of jets of various owners of rolling stock, delivering products of various nomenclatures and the *i*th number of E elements (trains, cars, marine vessels) involved in the carriage.

The difficulty of managing green supply chains lies in the insufficiently studied interrelations of indicators and parameters of logistics flows, in the absence of comprehensive assessment methods for many parameters and indicators of logistics flows. For example, making decisions to ensure timely delivery can lead to an increase in uneven flow of goods, which will negatively affect the energy intensity of the entire logistics process and the volume of greenhouse gas emissions. On the other hand, the desire to increase the coefficient of discreteness of the flow (to reduce the size of the transport-cargo parties) allows achieving a more uniform advancement of the flow, but leads to an increase in transport costs.

The authors propose a new approach to the management of green supply chains, based on the use of the original system of parameters and indicators to evaluate the parameters of logistics flows for compliance with the principles of sustainable development (Table 7). Five groups of parameters and indicators of logistics flows in green supply chains have been identified:

- the group of controlled (physical) parameters of logistic flows, characterizing the intensity of flows and the properties of changes in flows in space and time;
- the group of economic parameters of logistic flows characterizing the efficiency of use of all types of resources of the logistics system, as well as the degree of economic viability of the logistics system;
- the group of energy and environmental parameters characterizing the efficiency of energy use in the process of promoting flows and the impact of logistics flows on the environment;
- the group of parameters for quality assessment, characterizing the safety and timeliness of the promotion and processing of flows, as well as the quality of duct management;
- the group of statistical parameters, reflecting the patterns of change in the controlled parameters of flows.

Table 7 System of parameters and indicators of logistic flows in green supply chains

Group of parameters or indicators	Name of parameter or indicator	Characteristic
Group of controlled (physical) flow parameters	The mass (quantity) of flow	The total mass (number) of flow elements in motion along the flow route
	The length of the route	The total distance (the sum of the lengths of the $n - 1$ vectors that make up the route) that the flow element travels along the route
	The speed of flow	The ratio of the length of the route to the time of movement of the stream along the route (averaged characteristic of the speed of the jets of flow)
Group of economic indicators	Profit	The difference between total revenue and operating expenses
	Operating expenses	The sum of all types of expenses associated with the conversion of investments into profits
	Fixed investment	The amount of cash spent on the formation of fixed assets
The group of energy and environmental parameters	The energy intensity	The amount of energy spent on promoting the flow along the route
	Greenhouse gas emissions of CO_2	Total greenhouse gas emissions from all sources involved in promoting flow
The group of parameters for quality assessment	Safety of cargo transportation	Indicators characterizing transportation without damage, without pollution, without loss
	Timeliness of cargo transportation	Indicators characterizing the transportation of goods by the deadline, the frequency of arrival of goods and the urgency of transportation

(continued)

Table 7 (continued)

Group of parameters or indicators	Name of parameter or indicator	Characteristic
	The coefficient of flow controllability	The ratio of the mass of the information flow, the elements of which are messages on the indicators observance of transportation safety and timeliness, to the mass of the control information flow (the number of information-control messages)
The group of statistical parameters	The coefficient of flows irregularity	The deviation of the values of the physical parameters of the flows (jets, elements) from their average values
	The coefficient of flow structure complexity	It characterizes the number of jets that make up the logistic flow
	The coefficient of flow discreteness	It characterizes the number of elements that the flow consists of. It is calculated as the ratio of the time interval between flow elements to the minimum non-zero value of the interval at which the flow is considered continuous
	The coefficient of flow differentiability	It characterizes the change in the complexity of the flow structure in the process of its movement along the route. It is calculated as the ratio of the number of jets of the stream at the final point of the route of advancement of the flow to the number of jets at the starting point

The developed system of parameters and indicators of logistic flows in green supply chains is used in the proposed management system to evaluate flows and develop management decisions to change these parameters in order to achieve the goal of functioning of the green supply chain and the goals of the sustainable development concept as a whole.

6 Evaluation of Parameters and Indicators of Logistic Flows Using the Fuzzy AHP-TOPSIS Method

The values assessment of parameters and indicators of logistic flows in green supply chains is carried out in order to increase the efficiency of using green logistics instruments (green technologies) to ensure the sustainability of supply chains. In the present, the fuzzy AHP-TOPSIS combined method was used to perform this assessment.

The first use of fuzzy AHP based on triangular fuzzy numbers and the extent analysis method was described in [127] fuzzy AHP approach was presented by Chang [127], triangular fuzzy number (TFN) are preferred for pair wise comparison scale of fuzzy AHP and extent analysis method was used for the synthetic extent value of pair wise comparison. Later, the application of the fuzzy AHP approach is justified for solving the problems of sustainable transportation systems [128, 129], supply chain management [130, 131] and reverse logistics [132].

Using fuzzy AHP, unlike the basic method of hierarchy analysis (AHP) proposed by Tomas L. Saaty [133], eliminates such disadvantages as [134, 135]: unbalanced judgment scales, uncertainty, inaccuracy and subjectivity expert judgment, and ensure accuracy of ranking.

Since the authors have identified a lot of unsystematically applied instruments of green logistics, the problem arises of assessing the effectiveness of each instrument, that is, determining how the parameters and indicators of logistics flows change as a result of using one or another instrument. In fact, this task boils down to ranking the instruments in terms of efficiency. According to the authors, the best solution to this problem is achieved by using the fuzzy TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution)—a fuzzy method for determining the sequence number (or rank) of a solution depending on its proximity to the ideal solution. The TOPSIS approach chooses alternative that is closest to the positive ideal solution and farthest from the negative ideal solution. The “decision” in this study refers to the choice of a particular green logistics instrument.

For the first time, the use of the TOPSIS method was proposed in [136] with the goal of selecting the best alternative with a finite number of criteria. In [137, 138] presented a review of scientific publications in the field of using the TOPSIS method for solving various problems, among which the largest share falls on supply chain management and logistics and design, engineering and manufacturing systems. A number of works [131, 139–141] substantiate the use of fuzzy TOPSIS to solve multi criteria decision making problems under fuzzy environment and to manage with uncertainty in the judgments and evaluations of the decision makers.

The combination of AHP-TOPSIS methods allows you to improve the quality of assessment of decision makers in the selection and implementation of green logistics instruments. fuzzy AHP is used to determine the weight of parameters and indicators of logistic flows, and fuzzy TOPSIS is used to rank green logistics instruments, considering the influence of each instrument on these parameters and indicators.

Table 8 The system of parameters and indicators of logistics flows

Group of flow parameters (I hierarchy level)		Flow indicators (II level of hierarchy)	
Group of economic flow parameters	E	Profit	EI1
		Operating expenses	EI2
		Fixed investment	EI3
The group of energy and environmental parameters	EE	The energy intensity	EEI1
		Greenhouse gas emissions of CO_2	EEI2
The group of parameters for quality assessment	S	Safety of cargo transportation	SI1
		Timeliness of cargo transportation	SI2
		The coefficient of flow controllability	SI2
The group of statistical parameters	ST	The coefficient of flows irregularity	ST1
		The coefficient of complexity structure of flow	ST2
		The coefficient of flows discreteness	ST3
		The coefficient of differentiability of flow	ST4
Group of controlled (physical) flow parameters	M	The mass (quantity) of flow	MI1
		The speed of flow	MI2
		The length of the route	MI3

In order to use fuzzy AHP, it is necessary to present a system of parameters and indicators of logistic flows in the form of a multi-level hierarchical model. The components of the first level of the hierarchy are groups of parameters of logistics flows that correspond to the main aspects of the concept of sustainable development. The components of the second level of the hierarchy are 15 parameters and indicators of logistic flows (Table 8), the description of which is presented in paragraph 6 of this work.

The use of a triangular function, which is given by the relation:

$$\mu_M(x) = \begin{cases} 0, 0 \leq x \leq a \\ \frac{x-a}{b-a}, a \leq x \leq b \\ \frac{c-x}{c-b}, b \leq x \leq c \\ 0, c \leq x. \end{cases}, \tag{1}$$

where a is the left zero; b is the point at which the value of the membership function is 1; c is the right zero (Fig. 13).

Based on a summary of the studies [129, 131, 141] in this work, linguistic variables and triangular fuzzy numbers are accepted for evaluating the parameters and indicators of logistic flows (Table 9).

The construction of matrices for pair wise comparisons $\tilde{A}(\tilde{u}_{ij})$ is performed for all parameters and indicators of logistics flows in order to determine the relative importance of each pair of parameters (indicators) among themselves.

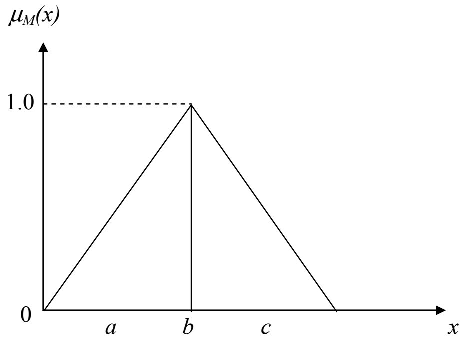


Fig. 13 Triangular membership function

Table 9 Fuzzy and linguistic variables for evaluating parameters and indicators of logistic flows

Fuzzy number	Linguistic term	Scale of fuzzy number
1	Equal importance	(1, 1, 3)
2	Moderate superiority	(1, 3, 5)
3	Significant superiority	(3, 5, 7)
4	Strong superiority	(5, 7,9)
5	Absolute superiority	(7, 9, 10)

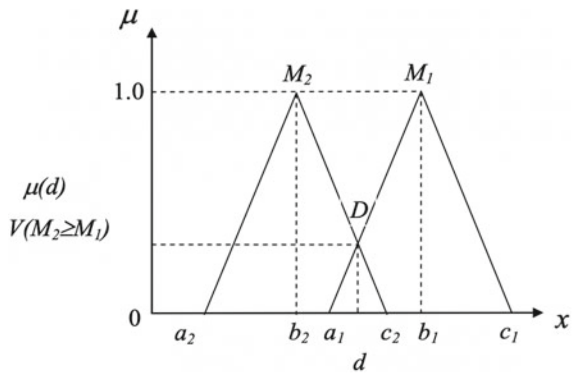
$$\tilde{A} = \begin{bmatrix} 1 & \tilde{u}_{12} & \tilde{u}_{13} & \cdots & \tilde{u}_{1(n-1)} & \tilde{u}_{1n} \\ \tilde{u}_{21} & 1 & \tilde{u}_{23} & \cdots & \tilde{u}_{2(n-1)} & \tilde{u}_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \tilde{u}_{(n-1)1} & \tilde{u}_{(n-1)2} & \tilde{u}_{(n-1)3} & \cdots & 1 & \tilde{u}_{(n-1)n} \\ \tilde{u}_{n1} & \tilde{u}_{n2} & \tilde{u}_{n3} & \cdots & \tilde{u}_{n(n-1)} & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{u}_{12} & \tilde{u}_{13} & \cdots & \tilde{u}_{1(n-1)} & \tilde{u}_{1n} \\ 1/\tilde{u}_{12} & 1 & \tilde{u}_{23} & \cdots & \tilde{u}_{2(n-1)} & \tilde{u}_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1/\tilde{u}_{1(n-1)} & 1/\tilde{u}_{2(n-1)} & 1/\tilde{u}_{3(n-1)} & \cdots & 1 & \tilde{u}_{(n-1)n} \\ 1/\tilde{u}_{1n} & 1/\tilde{u}_{2n} & 1/\tilde{u}_{3n} & \cdots & 1/\tilde{u}_{(n-1)n} & 1 \end{bmatrix}, \tag{2}$$

where

$$\tilde{u}_{ij} = \begin{cases} 1, i = j \\ 9^{-1}, 8^{-1}, 7^{-1}, 6^{-1}, 5^{-1}, 4^{-1}, 3^{-1}, 2^{-1}, 1^{-1}, 1, 2, 3, 4, 5, 6, 7, 8, 9, i \neq j \end{cases} \tag{3}$$

The values of fuzzy synthetic extent with respect to ith criterion is defined as

Fig. 14 The intersection between two fuzzy numbers M_1 and M_2



$$S_i = \sum_{j=1}^{m} \tilde{u}_{ij} \left[\sum_{i=1}^{n} \sum_{j=1}^{m} \tilde{u}_{ij} \right]^{-1}, \tag{4}$$

where

$$\sum_{j=1}^{m} \tilde{u}_{ij} = \left(\sum_{j=1}^{m} a_j, \sum_{j=1}^{m} b_j, \sum_{j=1}^{m} c_j \right), \tag{5}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} \tilde{u}_{ij} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} c_i}, \frac{1}{\sum_{i=1}^{n} b_i}, \frac{1}{\sum_{i=1}^{n} a_i} \right) \tag{6}$$

To obtain the estimates for the vectors of weights under each criterion, we need to consider a principle of comparison for fuzzy numbers (Fig. 14).

The degree of possibility of $M_2 = (a_2, b_2, c_2) > M_1 = (a_1, b_1, c_1)$ is defined as

$$V(M_2 \geq M_1) = \sup\left[\min\left(\mu_{M1(x)}, \mu_{M2(y)}\right)\right] = hgt(M_1 \cap M_2) = \mu_{M2(d)}, \tag{7}$$

$$\mu_M(d) = \begin{cases} 1, & if \quad b_2 \geq b_1 \\ 0, & if \quad a_1 \geq c_2 \\ \frac{a_1 - c_2}{(b_2 - c_2) - (b_1 - a_1)} & otherwise \end{cases}, \tag{8}$$

where d is the ordinate of the highest intersection point D between $\mu_{M1(x)}$ and $\mu_{M2(y)}$.

To compare M_1 and M_2, both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are needed.

The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i (i = 1, 2, 3, \ldots, k)$ can be defined by

$$V(M \geq M_1, M_2, \ldots, M_k) = V\big[(M \geq M_1)\ and\ (M \geq M_2)\ and \ldots and\ (M \geq M_k)\big] \\ = \min V(M \geq M_i), i = 1, 2, \ldots, k. \quad (9)$$

Assume that

$$d'(A_i) = \min V(S_i \geq S_k), \quad for \quad k = 1, 2, \ldots, n; \quad k \neq i. \quad (10)$$

Then the weight vector is given by

$$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T, \quad (11)$$

where $A_i (i = 1, 2, 3, \ldots, n)$ vector of estimated parameters consisting of n elements.

Via normalization, the normalized weight vectors are

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T, \quad (12)$$

where W is a nonfuzzy number.

Thus, the result of applying the fuzzy AHP method is the weight of parameters and indicators of logistics flows in supply chains. These results are further used in the construction of a fuzzy model of logistics flows in supply chains (Sect. 7).

The fuzzy TOPSIS method is used to rank green logistics instruments by the degree of their influence on the performance of logistics flows in supply chains. In general, the sequence of stages of the execution of fuzzy TOPSIS includes the following actions [138, 141]:

1. Formation of decision matrix and rating criteria and alternatives.
2. Determination of criteria weight using various methods.
3. Normalization of the fuzzy solutions matrix.
4. Calculation of a weighted normalized matrix of fuzzy solutions.
5. Calculation of the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS).
6. Determining the distances from each alternative to FPIS and FNIS.
7. Calculation of the proximity coefficient CC_i for each alternative.
8. Ranking alternatives and choosing the best alternative.

The developed methodology for implementing the fuzzy TOPSIS method for solving the problem of ranking green logistics instruments includes the following steps.

1. Assigning ratings to criteria and alternatives. Suppose that there are m possible alternatives, called $I = \{I_1, I_2, I_3, \ldots, I_m\}$ alternatives, which are evaluated according to criteria $C = \{C_1, C_2, C_3, \ldots, C_n\}$ by a group of k decision makers $D = \{D_1, D_2, D_3, \ldots, D_k\}$.

Table 10 Green logistics instruments (for example, a transport element)

Instrument name	Designation
The selection of environmentally friendly modes of transport	I_1
The use of intermodal technologies and multimodal transport	I_2
Vehicles with the least impact on the environment	I_3
Selection of vehicles with larger carrying capacity (cargo capacity)	I_4
Environmentally friendly fuels and lubricants (fuels)	I_5
Provision of technological unity for transport and warehouse process	I_6
Optimization of traffic route of vehicles movement	I_7
Optimization of vehicles' speed	I_8
Eco-driving	I_9
Consolidation of traffic flows to the directions	I_{10}
Optimization of traffic flows structure	I_{11}
Operational management of material flows' parameters in order to ensure uniform load of transport infrastructure elements and decrease congestion and stocks	I_{12}

$$D = \begin{array}{c} \\ I_1 \\ I_2 \\ \vdots \\ I_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_1 & \cdots & C_1 \end{array} \\ \begin{pmatrix} r_{11} & r2 & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} \end{array}, \tag{13}$$

where r_{mn} is the rating of alternatives I_m according to the criterion C_n, estimated by the k-th decision maker.

The green logistics instruments act as alternatives (Table 10).

2. Calculation of cumulative fuzzy scores for criteria and alternatives. If fuzzy estimates of all decision-makers are described as a triangular fuzzy number (Table 11), then the assessment of each criterion is determined by the formulas

Table 11 Linguistic variables and triangular fuzzy numbers for green instrument rating

Fuzzy number	Linguistic term	Triangular fuzzy number
1	Very poor	(1, 1, 3)
2	Poor	(1, 3, 5)
3	Fair	(3, 5, 7)
4	Good	(5, 7, 9)
5	Very good	(7, 9, 10)

$$a_{mnk} = \min_k\{a_{mnk}\},$$

$$b_{mnk} = \frac{1}{K}\sum_K^1 b_{mnk}, \tag{14}$$

$$c_{mnk} = \max_k\{c_{mnk}\}.$$

3. Normalization of the fuzzy solutions matrix. The normalized matrix of fuzzy solutions will take the following form $R = \left[r_{ij}\right]_{m \times n}, \quad i = 1, 2, 3 \ldots, m; \quad j = 1, 2, 3 \ldots, n$

$$\text{benefit criteria}: r_{ij} = \left(\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+}\right) \quad u \quad c_j^+ = \max_i\left\{c_{ij}\right\}, \tag{15}$$

$$\text{cost criteria}: r_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{c_{ij}}, \frac{a_j^-}{c_{ij}}\right) \quad u \quad a_j^- = \min_i\left\{a_{ij}\right\}. \tag{16}$$

4. Calculation of a weighted normalized matrix. The weighted normalized matrix V is determined by the product of the weights of the evaluation criteria (w_j) by the normalized matrix of fuzzy solutions (r_{ij})

$$\begin{aligned} &V = \left[v_{ij}\right]_{m \times n}, \quad i = 1, 2, 3 \ldots, m; \quad j = 1, 2, 3 \ldots, n, \\ &V = r_{ij} \times w_j, \\ &\sum\nolimits_{i=1}^{n} w_j = 1. \end{aligned} \tag{17}$$

5. Calculation of a fuzzy positive ideal solution (FPIS) and a fuzzy negative ideal solution (FNIS)

$$A^+ = \left(v_1^+, v_2^+, \ldots, v_n^+\right), \quad v_j^+ = \max_i\left\{v_{ij}\right\} 1, 2, 3 \ldots, m; \quad j = 1, 2, 3 \ldots, n, \tag{18}$$

$$A^- = \left(v_1^-, v_2^-, \ldots, v_n^-\right), \quad v_j^- = \min_i\left\{v_{ij}\right\} 1, 2, 3 \ldots, m; \quad j = 1, 2, 3 \ldots, n. \tag{19}$$

6. Calculation of the distance of each alternative from FPIS and FNIS. The calculation of the distance (d_i^+,d_i^-) of each alternative A^+ and A^- is carried out according to the formulas

$$d_i^+ = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^+ \right)^2 \right\}^{\frac{1}{2}}, \quad i = 1, 2, 3 \ldots, m, \tag{20}$$

$$d_i^- = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2 \right\}^{\frac{1}{2}}, \quad i = 1, 2, 3 \ldots, m. \tag{21}$$

7. Calculation of the closeness coefficient CC_i of each alternative. The proximity coefficient CC_i represents the distances to a fuzzy positive ideal solution (A^+) and a fuzzy negative ideal solution (A^-) at the same time

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+}, \quad i = 1, 2, 3 \ldots, m \tag{22}$$

8. Ranking alternatives. Alternatives are ranked according to proximity coefficient (CC_i) in descending order. The best alternative is the one closest to FPIS and the farthest from FNIS.

7 Fuzzy Model of Logistics Flows in Green Supply Chains

The fuzzy model of logistic flows in green supply chains described in this section is used for an integrated assessment of the supply chain's compliance with the goals of the concept of sustainable development. The value of the integral indicator of the sustainability of the supply chain is determined on the basis of a fuzzy assessment of the performance of logistics flows, taking into account the weight of these indicators calculated by the fuzzy AHP method.

The developed fuzzy model of logistics flows in green supply chains consists of the following elements: a diagram of the relationship of parameters and indicators of logistics flows; basic values of parameters and indicators for various modes of transport and transport system type; a set of membership functions for terms of linguistic variables that describe the parameters and indicators of logistics flows; a set of logical control rules.

A relationship diagram of parameters and indicators in the developed fuzzy model of logistics flows in green supply chains is presented in Fig. 15.

The proposed model contains three fuzzy input variables that correspond to the physical parameters of the flow—mass, flow velocity and length of its route. The values of the input variables are introduced into the model taking into account statistical data obtained on the basis of the analysis of the supply chain. Three intermediate

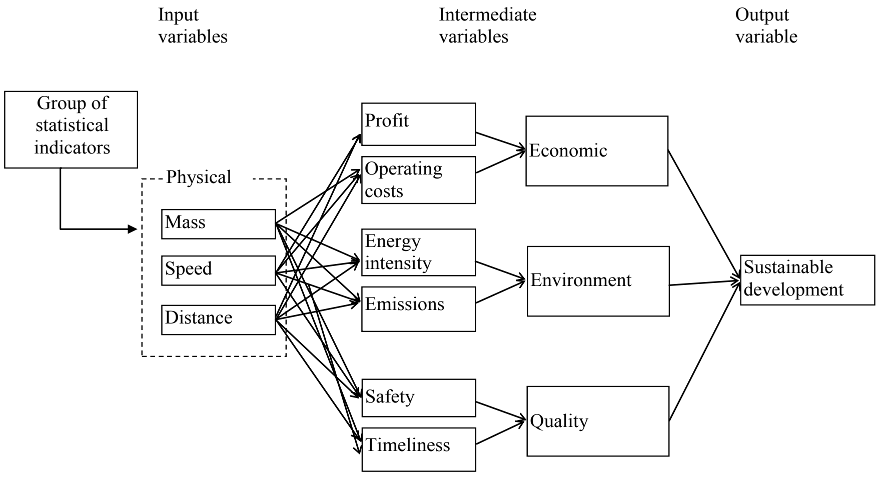


Fig. 15 Diagram of a fuzzy model for evaluating the parameters of logistics flows in green supply chains

groups of indicators are used as intermediate fuzzy linguistic variables—economic ("Economic"), energy-ecological ("Environment"), and quality indicators ("Quality"). Each group of indicators consists of two indicators, in accordance with Table 8. The output variable is the sustainability of the logistics flow.

The basic values of the parameters and indicators of logistic flows included in the fuzzy model depend on the transport type and the transport system type for which a specific fuzzy model is built. Basic values (ranges of values) of parameters and indicators of logistics flows for various modes of transport are presented in Tables 12, 13 and 14.

In the present study the national transport system was chosen as an example, within which the supply chain operates in inter-regional communication. The basic value of the "route length" parameter for such supply chains is presented in Table 15.

Table 12 The indicator value of logistics flows for various modes of transport[a]

Indicator	Truck	Railroad	Inland vessel	Aircraft
Profit (profitability), %	0–100			
Operating expenses	Average	Low	Low	High
Greenhouse gas emissions of CO_2, g/tkm	104	31	35	2030
The energy intensity, liter/100 tkm (at the rate of 1 L of gasoline—8.78 kW h of electricity)	5.1–9.2	0.7–1.0	0.6–1.4	51–73
Cargo transportation safety factor	0–1.0			
The coefficient of timeliness of transportation of goods	0–1.0			

[a]Based on [22, 36, 142, 143]

Table 13 The value of the parameter "mass of the logistic flow" for various modes of transport

Type of dispatch	Modes of transport			
	Truck	Railroad	Inland vessel	Aircraft
Small (small part)	10 kg < m < 5 t (or qγ/2)	20 kg < m < 20 t	m < 20 t	10–45 kg
Light tonnage	–	10-20 t	–	–
Large part	q auto (to 44 t)	–	–	–
Combined delivery	–	–	20 t	–
Carriage	–	q railway carriage		–
Ship	–	–	21,412 containers	–
Charter	–	–	–	to 130 t
Group	–	q wagon < m < Q route	–	–
Route	–	Q route (to 8050 t)	–	–

Table 14 The value of the parameter "logistic flow rate" for various modes of transport

Indicator	Modes of transport			
	Truck	Railroad	Inland vessel	Aircraft
Technical speed, km/h	15–60	35–45	25–35	450
The average speed of cargo delivery, km/day	450	260–370	280–300	10,000

Table 15 The value of the parameter "length of the route of the logistic flow" for various modes of transport

Indicator	Short	Average	Farther
Distance, km	10–200	200–800	800–2000

The type and parameters (definition domain) of membership functions for terms of linguistic variables [144, 145], describing the parameters and indicators of the developed fuzzy model, were determined by experts with knowledge in this field. In the process of debugging the model, as well as when changing the appearance of the transport system or supply chain, the type and parameters of membership functions can change.

In order to form a set of logical rules for the management of "if … then" the authors used the following rule, most often used in fuzzy choice systems

$$\text{Rule} < \# >\text{: IF} \ll \beta_1 \text{ is } a' \gg \text{, THEN} \ll \beta_2 \text{ is } a'' \gg .$$

The fuzzy saying «β_1 *is* a'» is a condition of this rule, and the fuzzy saying «β_2 *is* a''» is a fuzzy conclusion of this rule. A set of fuzzy inference rules is intended to formally represent empirical knowledge or expert knowledge. Such a set is usually presented in structured text form:

RULE_1: IF «*Condition_1*» THEN «*Conclusion_1*» (F_1);
RULE_2: IF «*Condition_2*» THEN «*Conclusion_2*» (F_2);
RULE_n: IF «*Condition_n*» THEN «*Conclusion_n*» (F_n).

Minimization of the deviation of the results of the logistic conclusion from the experimental data, that is, an increase in the accuracy of the results of the fuzzy model is ensured by its training, that is, an iterative change in the form and parameters of the membership functions of the fuzzy terms.

The fuzzyTECH program [145, 146] was chosen as an instrument for implementing the developed fuzzy model of parameters and indicators of logistic flows in green supply chains. This program is focused on solving the problems of modeling various objects and processes using the methods of the theory of fuzzy sets and fuzzy logic. The choice of the fuzzyTECH program is due to the presence in it, in addition to the standard for such a group of programs, fuzzy inference functions, and additional functions for generating program code for implementing the fuzzy inference system in one of the programming languages. The resulting software listings can when compiled in other computing platforms. This function is important for the development of the developed system for managing logistics flows in green supply chains by integrating a fuzzy inference system into a simulation model of logistics flows. It is assumed that such integration will automate the process of training and adjusting the fuzzy model with changes in the managed transport system or supply chain, and will also improve the accuracy of the fuzzy inference system.

8 Formation of a Logistics Flow Management System in Transport and Logistics Companies

The green logistics instruments presented in the previous sections, the selected parameters and indicators of logistics flows in the green supply chains, the method of estimating the weight of parameters and indicators of logistics flows—fuzzy-AHP and the ranking method of these parameters and indicators—fuzzy TOPSIS, a fuzzy model of the relationship of parameters and indicators—are the elements of a developed logistics flow management system.

The management process consists in monitoring the actual values of the parameters and indicators of logistics flows with the subsequent selection and implementation of green logistics instruments [40] in order to ensure the sustainability of the supply chain, that is, the compliance of its indicators with the goals of the concept of sustainable development. It is assumed that the result of the implementation of each instrument is a change in a certain combination of controlled parameters of logistics flows [47].

The presence of a wide variety of types of transport systems and supply chains makes it necessary to build a logistics flow management system that considers the specifics of these objects. The authors have developed a universal technique for the formation of a system for managing logistics flows, which includes the following steps (Fig. 16):

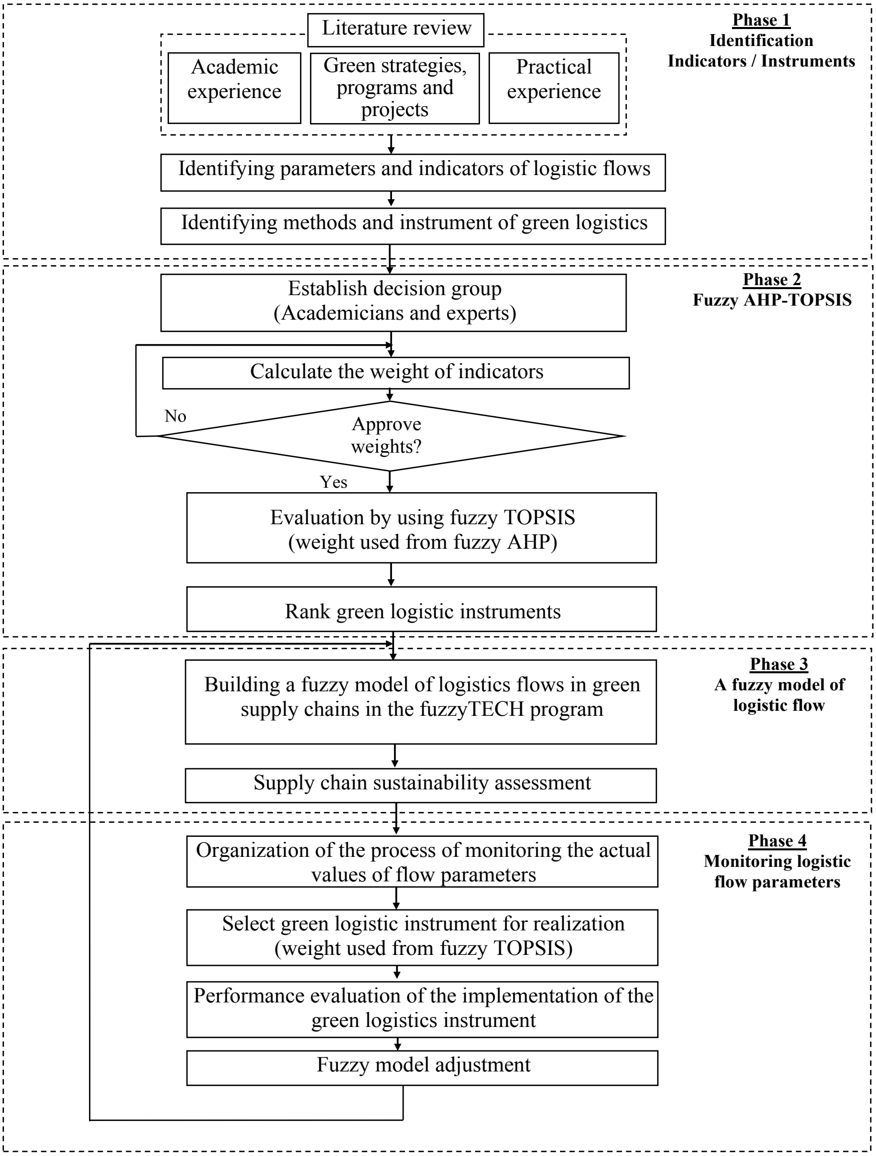


Fig. 16 Formation methodology for the system of managing the parameters of logistics flows in green supply chains

Stage 1. Refinement of parameters and indicators of logistic flows for a particular transport system or supply chain and selection of specific green logistics instruments. In most cases, it is recommended to use the system of green logistics instruments presented in Sect. 3 (Table 2) and the system of parameters and indicators of logistics flows presented in Sect. 5 (Table 7).

Stage 2. Ranking using fuzzy AHP-TOPSIS green logistics instruments according to the degree of influence on the performance of logistic flows.

Stage 3. Building a fuzzy model of logistics flows in green supply chains in a fuzzyTECH environment.

Stage 4. Organization of the process of monitoring the actual values of flow parameters with the subsequent selection using a fuzzy model of a specific instrument for green logistics. Implementation of the selected instrument, evaluation of the results and the actual effectiveness of the implemented instrument. Adjustment of the fuzzy inference model is repetition of the 3rd stage.

Since the methodology for performing the first and second stages is described in detail in Sect. 6, and the description of the fuzzy model (the third stage) for managing the parameters of logistics flows in green supply chains is described in Sect. 7, in more detail we will consider the contents of the fourth stage of the formation of a system for managing the parameters of logistics flows in green supply chains.

1. Based on the monitoring of supply chain logistics flows, the actual values of their indicators I_k are determined, where $k = 1,2, \ldots, K$, is the number of analyzed parameters and indicators of logistics flows.
2. The numerical actual values of the parameters and indicators of flows I_k are used as input in a fuzzy model of logistics flows to assess the sustainability of the supply chain. Figure 17 shows an example of a fuzzy model for estimating the parameters of logistic flows in fuzzyTECH for the selected supply chain at the level of the national transport system.
3. The results of modeling the relationship of parameters and flow indicators in a fuzzy model of logistic flows in green supply chains in fuzzyTECH are:

   - the value of the integral indicator of supply chain sustainability;
   - a surface describing the dependence of the integral indicator of the sustainability of the supply chain on changes in the values of physical parameters of material flows (mass, speed and route length), which are manageable in the developed control system.

4. Improving the sustainability of the supply chain is ensured by the implementation of green logistics instrument. The choice of an instrument is based on their rank, obtained by using the fuzzy AHP-TOPSIS methods.
5. As a result of applying the selected instrument, the values of the controlled parameters of the logistic flows change. The obtained value of these parameters is introduced into the model in order to assess the effectiveness of the selected instrument and its actual impact on the sustainability of the supply chain. Based on the results of evaluating the effectiveness of the implemented instrument, the model of the fuzzy choice is adjusted.

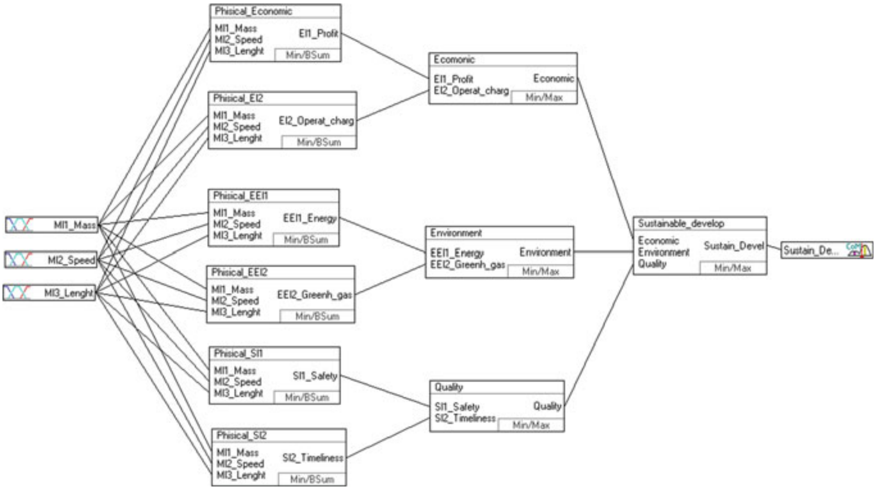


Fig. 17 Presentation of a fuzzy model for evaluating the parameters of logistics flows in the fuzzyTECH program

In the process of creating a system for managing logistics flows in green supply chains, the 5th stage of the presented methodology for implementing the fuzzy inference model can be implemented using a simulation model of the supply chain. Using the simulation model in the formation of the flow management system allows you to effectively train a fuzzy model of logistics flows, and in the process of operating the formed control system, you can predict changes in the parameters and indicators of logistics flows and plan, based on forecasts, the optimal sequence of implementation of green logistics instruments.

9 An Example of Using the Methodology for Managing the Parameters of Logistics Flows in Green Supply Chains

In the presented example, the supply chain operating within the national transport system is used as the control object.

1. Based on the literature review and practice of implementing green logistics instruments in supply chain management, 12 green logistics instruments were selected (Table 10). Assessment of logistics flows was carried out according to 5 groups of parameters and 15 indicators in accordance with aspects of the concept of sustainable development (Table 8).
2. As academic decision makers, 7 academic experts were selected. The experts evaluated the parameters and indicators of logistic flows using linguistic variables

and triangular fuzzy numbers. The final results of fuzzy AHP in the form of the fuzzy aggregated decision matrix for evaluating the parameters and indicators of logistic flows with weighting coefficients are presented in Tables 16, 17, 18, 19, 20 and 21. Designations of parameters and indicators of logistics flows are adopted in accordance with Table 8.

As an example, the calculation of the value of the fuzzy synthetic extent (The extent) according to the Formulas (4–6) for the groups of parameters of the logistics flows (Table 22).

The results of calculated degree of possibility of criteria (V-values) using Formulas 7–8 for groups of logistic parameters are presented in Table 23.

The degree of possibility for each parameter is calculated by Formula (9).

Table 16 Calculated fuzzy aggregated decision matrix of logistic flow parameters

Parameters	E	EE	S	ST	M	Weight	Rank
E	(1, 1, 1)	(1.12, 1.85, 2.69)	(0.19, 0.27, 0.43)	(3.97, 6.20, 8.27)	(0.19, 0.29, 0.46)	0.2538	2
EE	(0.37, 0.54, 0.89)	(1, 1, 1)	(1.37, 2.09, 4.11)	(2.44, 3.51, 5.92)	(0.21, 0.32, 0.58)	0.2219	4
S	(2.17, 3.47, 5.05)	(0.24, 0.43, 0.73)	(1, 1, 1)	(2.17, 2.76, 5.23)	(0.85, 1.26, 2.47)	0.2474	3
ST	(0.12, 0.16, 0.25)	(0.17, 0.28, 0.41)	(0.19, 0.36, 0.46)	(1, 1, 1)	(0.32, 0.39, 0.86)	0.0005	5
M	(2.17, 3.48, 5.05)	(1.72, 3.08, 4.64)	(0.40, 0.79, 1.17)	(1.15, 2.56, 3.11)	(1, 1, 1)	0.2764	1

Table 17 Calculated fuzzy aggregated decision matrix of economic indicators of logistics flows

Indicators	EI1	EI2	EI3	Weight	Rank
EI1	(1, 1, 1)	(2.27, 3.64, 4.96)	(1.58, 2.86, 4.11)	0.7572	1
EI2	(0.20, 0.27, 0.44)	(1, 1, 1)	(0.43, 0.69, 1.16)	0.0151	3
EI3	(0.24, 0.35, 0.63)	(0.86, 1.46, 2.30)	(1, 1, 1)	0.2277	2

Table 18 Calculated fuzzy aggregated decision matrix of energy and environmental indicators of logistics flows

Indicators	EEI1	EEI2	Weight	Rank
EEI1	(1, 1, 1)	(1.87, 3.31, 5.24)	0.9862	1
EEI2	(0.19, 0.30, 0.53)	(1, 1, 1)	0.0138	2

Table 19 Calculated fuzzy aggregated decision matrix of quality indicators of logistics flows

Indicators	SI1	SI2	SI3	Weight	Rank
SI1	(1, 1, 1)	(1.27, 1.70, 2.30)	(0.85, 1.72, 2.86)	0.4478	1
SI2	(0.43, 0.59, 0.79)	(1, 1, 1)	(0.72, 1.40, 2.09)	0.0349	3
SI3	(0.35, 0.58, 1.17)	(0.48, 0.71, 1.39)	(1, 1, 1)	0.2473	2

Table 20 Calculated fuzzy aggregated decision matrix of statistical indicators of logistics flows

Indicators	STI1	STI2	STI3	STI4	Weight	Rank
STI1	(1, 1, 1)	(1.47, 2.02, 2.43)	(1.04, 1.72, 2.36)	(1.26, 1.81, 2.17)	0.4116	1
STI2	(0.41, 0.49, 0.68)	(1, 1, 1)	(0.87, 1.54, 2.45)	(1.37, 2.17, 2.76)	0.3290	2
STI3	(0.42, 0.58, 0.96)	(0.41, 0.65, 1.13)	(1, 1, 1)	(0.96, 1.17, 1.51)	0.1747	3
STI4	(0.46, 0.55, 0.79)	(0.36, 0.46, 0.73)	(0.66, 0.85, 1.04)	(1, 1, 1)	0.0846	4

Table 21 Calculated fuzzy aggregated decision matrix of managed logistics flow parameters

Indicators	MI1	MI2	MI3	Weight	Rank
MI1	(1, 1, 1)	(0.95, 1.29, 1.90)	(1.70, 2.57, 3.96)	0.4507	2
MI2	(0.53, 0.78, 1.05)	(1, 1, 1)	(2.36, 4.53, 6.59)	0.5447	1
MI3	(0.25, 0.39, 0.59)	(0.15, 0.22, 0.42)	(1, 1, 1)	0.0046	3

Table 22 Values of fuzzy synthetic extent

Parameters	$\sum_{j=1}^{m} \tilde{u}_{ij} = \left(\sum_{j=1}^{m} a_j, \sum_{j=1}^{m} b_j, \sum_{j=1}^{m} c_j\right)$	$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} \tilde{u}_{ij}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} c_i}, \frac{1}{\sum_{i=1}^{n} b_i}, \frac{1}{\sum_{i=1}^{n} a_i}\right)$	S_i
E	(6.4773, 9.6169, 12.8589)	(1/57.8058, 1/39.1306, 1/26.5671)	(0.11205, 0.24576, 0.48402)
EE	(5.4023, 7.4697, 12.5095)	(1/57.8058, 1/39.1306, 1/26.5671)	(0.09346, 0.19089, 0.47086)
S	(6.4337, 8.9299, 14.4818)	(1/57.8058, 1/39.1306, 1/26.5671)	(0.1113, 0.22821, 0.5451)
ST	(1.8021, 2.1975, 2.9859)	(1/57.8058, 1/39.1306, 1/26.5671)	(0.03118, 0.05616, 0.11239)
M	(6.4518, 10.9166, 14.9697)	(1/57.8058, 1/39.1306, 1/26.5671)	(0.11161, 0.27898, 0.56347)

Table 23 Calculated degree of possibility of criteria (V-values)

Parameters	E	EE	S	ST	M
E	–	1	1	1	0.91811
EE	0.86736	–	0.90598	1	0.80309
S	0.96104	1	–	1	0.89516
ST	0.00177	0.12322	0.00631	–	0.00349
M	1	1	1	1	–

$$d'(E) = \min V(S_i = S_k) = \min(1,\ 1,\ 1,\ 0.91811) = 0.91811.$$

For other parameters, the values will be equal $d'(EE) = 0.80309$, $d'(S) = 0.89516$, $d'(ST) = 0.00349$, $d'(M) = 1$.

The weight vector of each criteria is given by

$$W' = 0.91811, 0.80309, 0.89516, 0.00177, 1.$$

Via normalization of weight vector, the final weight vector obtained as

$$W = 0.25375, 0.22196, 0.24741, 0.00049, 0.27639$$

Similar calculations are carried out for each group of parameters of logistics flows. The final results of calculating the weighting coefficients of the parameters and indicators of logistics flows are presented in Table 24.

3. In order to rank the green logistics instruments using fuzzy TOPSIS, experts evaluated the instruments using triangular fuzzy numbers (Table 11).

In order to calculate the total matrix of fuzzy decisions, Formula (14) is used. The results of calculating the total fuzzy score for indicators of logistics flows and green logistics instruments are presented in Table 25.

Taking into account the criteria of benefit or cost, in accordance with Formulas (15) and (16), normalization of fuzzy decisions was performed (Table 26).

In order to calculate the weighted normalized matrix, we use the weight coefficients of the logistic flow indicators obtained as a result of applying the fuzzy AHP method (Table 24). The calculation results are presented in Table 27.

After determining the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS) using Formulas (18) and (19), the distance (d_i^+, d_i^-) for each alternative from FPIS and FNIS is calculated using the Formulas (20) and (21). Using the proximity coefficient (CC_i) calculated by Formula (22), the ranking of green logistics instruments is performed (Table 28).

The ranking results of green logistics instruments by their degree of impact on the parameters and indicators of logistics flows are used when choosing an instrument to adjust the actual values of the indicators of logistics flows in accordance with the requirements of the sustainable development concept.

Table 24 Final ranking parameters and indicators of logistics flows

Criterion	Weight	Sub-criteria	Weight	Finalized weight	Global Rank
Group of economic flow parameters (E)	0.2538	EI1	0.75726	0.19216	2
		EI2	0.01508	0.00383	9
		EI3	0.22766	0.05777	8
The group of energy and environmental parameters (EE)	0.2220	EEI1	0.98622	0.21890	1
		EEI2	0.01378	0.00306	10
The group of parameters for quality assessment (S)	0.2474	SI1	0.44784	0.11080	5
		SI2	0.30491	0.07544	6
		SI3	0.24725	0.06117	7
The group of statistical parameters (ST)	0.0005	ST1	0.41160	0.00020	12
		ST2	0.32903	0.00016	13
		ST3	0.17474	0.00009	14
		ST4	0.08463	0.00004	15
Group of controlled (physical) flow parameters (M)	0.2764	MI1	0.45068	0.12456	4
		MI2	0.54476	0.15056	3
		MI3	0.00456	0.00126	11

We try to consider, as an example, the implementation of the proposed methodology for managing the parameters of logistics flows in green supply chains. Transportation of goods in the supply chain between the cities of Moscow and Yekaterinburg (the Russian Federation) is carried out using road transport. Actual supply chain metrics are presented in Table 29.

By substituting the actual flow indicators into the developed fuzzy inference model, we obtained surfaces describing the influence of fuzzy values of the controlled parameters of logistic flows on the value of supply chain sustainability (Fig. 18).

Based on the analysis of the actual values of the flow indicators, indicators are selected that do not meet the environmental requirements: increased energy intensity; high greenhouse gas emissions. In order to bring the indicators of logistics flows in line with the required values, a green logistics instrument is selected.

The analysis of the possibilities of implementing green logistics instruments, as applied to the supply chain under consideration, allowed us to identify 4 instrument: optimization of speed (I_8); route optimization (I_7); use of vehicles with a higher carrying capacity (I_4); the use of environmentally friendly modes of transport (I_1). The implementation of the remaining green logistics instruments for the analyzed conditions is not advisable.

As a result of the possible implementation of each instrument, new values of the controlled parameters were determined (Table 30).

As an example Fig. 19 demonstrates surfaces that describe the effect of fuzzy values of the controlled parameters of logistics flows on the sustainability of the supply chain when implementing the instruments “Optimization of the route of movement”

Table 25 Calculated aggregate fuzzy decisions matrix of green logistics instruments

Green logistics instruments	Logistics flow indicators						
	EI1	EI2	EI3	…	MI1	MI2	MI3
I_1	(3, 5.67, 9)	(5, 7.67, 10)	(5, 8.33, 10)	…	(1, 5, 9)	(1, 5, 9)	(3, 5.67, 9)
I_2	(5, 7.67, 10)	(3, 6.33, 10)	(5, 7, 9)	…	(1, 4.33, 9)	(3, 6.33, 9)	(3, 7, 10)
I_3	(1, 4.33, 9)	(1, 5.67, 9)	(3, 6.33, 10)	…	(1, 3.66, 7)	(1, 3.67, 7)	(1, 3.67, 7)
I_4	(3, 5.67, 9)	(3, 7, 10)	(1, 6.33, 10)	…	(5, 7, 9)	(1, 3.67, 9)	(1, 1.67, 5)
I_5	(3, 5.67, 9)	(3, 6.33, 9)	(1, 3, 7)	…	(1, 1, 3)	(1, 2.33, 5)	(1, 1, 3)
I_6	(1, 5.67, 10)	(3, 7, 10)	(1, 5, 9)	…	(1, 3.67, 9)	(1, 5, 9)	(1, 3.67, 7)
I_7	(1, 5, 9)	(3, 5.67, 9)	(1, 3, 7)	…	(1, 2.33, 7)	(1, 5, 9)	(1, 5.67, 10)
I_8	(1, 5, 10)	(1, 5, 9)	(1, 1.67, 5)	…	(1, 2.33, 5)	(7, 9, 10)	(1, 3, 7)
I_9	(1, 2.33, 5)	(1, 3.67, 7)	(1, 1, 3)	…	(1, 1.67, 5)	(1, 5, 9)	(1, 2.33, 7)
I_{10}	(1, 4.33, 7)	(1, 5.67, 9)	(1, 1.67, 5)	…	(5, 7.66, 10)	(1, 5, 9)	(1, 5.67, 9)
I_{11}	(1, 5.67, 9	(1, 5, 9)	(1, 2.33, 5)	…	(3, 5, 7)	(1, 6.33, 10)	(1, 3.67, 7)
I_{12}	(1, 4.33, 9)	(1, 5, 9)	(1, 2.33, 5)	…	(1, 5, 9)	(3, 6.33, 9)	(3, 5.67, 9)

(the least sustainability is 0.1357) and "Use of environmentally friendly modes of transport" (the highest sustainability is 0.4027).

Thus, in order to bring the indicators of logistics flows in line with the required values, the most effective instrument is the "Use of environmentally friendly modes of transport" (transition from road to rail). The least effective is the "Vehicle route optimization" instrument.

10 Conclusion

For the effective implementation of the sustainable development concept in logistics and supply chain management, methods are needed to develop managerial decisions to change the parameters of logistics flows based on the measurement and evaluation

Table 26 Normalized fuzzy decisions matrix of green logistics instruments

Green logistics instruments	Logistics flow indicators				
	EI1	EI2	EI3	…	MI3
I_1	(0.3, 0.567, 0.9)	(0.2, 0.130, 0.1)	(0.5, 0.833, 1)	…	(0.333, 0.177, 0.111)
I_2	(0.5, 0.767, 1)	(0.333, 0.158, 0.1)	(0.5, 0.7, 0.9)	…	(0.333, 0.143, 0.1)
I_3	(0.1, 0,433, 0.9)	(1, 0.177, 0.111)	(0.3, 0.633, 1)	…	(1, 0.273, 0.143)
I_4	(0.3, 0.567, 0.9)	(0.333, 0.143, 0.1)	(0.1, 0.633, 1)	…	(1, 0.6, 0.2)
I_5	(0.3, 0.567, 0.9)	(0.333, 0.158, 0.111)	(0.1, 0.3, 0.7)	…	(1, 1, 0.333)
I_6	(0.1, 0.567, 1)	(0,333, 0.143, 0.1)	(0.1, 0.5, 0.9)	…	(1, 0.273, 0.143)
I_7	(0.1, 0.5, 0.9)	(0.333, 0.176, 0.111)	(0.1, 0.3, 0.7)	…	(1, 0.177, 0.1)
I_8	(0.1, 0.5, 1)	(1, 0.2, 0.111)	(0.1, 0.167, 0.5)	…	(1, 0.333, 0.143)
I_9	(0.1, 0.233, 0.5)	(1, 0.273, 0.143)	(0.1, 0.1, 0.3)	…	(1, 0429, 0.143)
I_{10}	(0.1, 0.433, 0.7)	(1, 0.176, 0.111)	(0.1, 0.167, 0.5)	…	(1, 0.177, 0.111)
I_{11}	(0.1, 0.567, 0.9)	(1, 0.2, 0.111)	(0.1, 0.233, 0.5)	…	(1, 0.273, 0.143)
I_{12}	(0.1, 0.433, 0.9)	(1, 0.2, 0.111)	(0.1, 0.233, 0.5)	…	(0.333, 0.177, 0.111)

of their indicators. As the analysis of scientific literature shows, the difficulty of managing green supply chains perform:

1. The lack of a universal system of logistics principles that ensure the formation of a balance between the economic, social and environmental sustainability of the logistics system;
2. A variety of approaches and views on the content of the methods and instruments of green logistics, which is the reason for the lack of systematic implementation in practical activities;
3. Lack of an integrated and systematic approach to the assessment of all types of logistics flows, based on taking into account the relationship between indicators and flow parameters from the perspective of the sustainable development concept.

The study presents the concept of managing logistics flows in green supply chains. The concept is based on the idea of achieving a balance between the economic, environmental and social sustainability of the logistics system or supply chain. The formation of such a system should be based on the following provisions:

Table 27 Weighted normalized fuzzy decisions matrix of green logistics instruments

Green logistics instruments	Logistics flow indicators				
	EI1	EI2	EI3	…	MI3
I_1	(0.0576, 0.1089, 0.1729)	(0.0008, 0.0005, 0.0004)	(0.0289, 0.0481, 0.0578)	…	(0.0004, 0.0002, 0.0001)
I_2	(0.0961, 0.1473, 0.1922)	(0.0013, 0.0006, 0.0004)	(0.0289, 0.0404, 0.052)	…	(0.0004, 0.0002, 0.0001)
I_3	(0.0192, 0.0833, 0.1729)	(0.0038, 0.0007, 0.0004)	(0.0173, 0.0366, 0.0578)	…	(0.0013, 0.0003, 0.0002)
I_4	(0.0576, 0.1089, 0.1729)	(0.0013, 0.0005, 0.0004)	(0.0058, 0.0366, 0.0578)	…	(0.0013, 0.0008, 0.0003)
I_5	(0.0576, 0.1089, 0.1729)	(0.0013, 0.0006, 0.0004)	(0.0058, 0.0173, 0.0404)	…	(0.0013, 0.0013, 0.0004)
I_6	(0.0192, 0.1089, 0.1922)	(0.0013, 0.0005, 0.0004)	(0.0058, 0.0289, 0.052)	…	(0.0013, 0.0003, 0.0002)
I_7	(0.0192, 0.0961, 0.1729)	(0.0013, 0.0007, 0.0004)	(0.0058, 0.0173, 0.0404)	…	(0.0013, 0.0002, 0.0001)
I_8	(0.0192, 0.0961, 0.1922)	(0.0038, 0.0008, 0.0004)	(0.0058, 0.0096, 0.0289)	…	(0.0013, 0.0004, 0.0002)
I_9	(0.0192, 0.0448, 0.0961	(0.0038, 0.001, 0.0005)	(0.0058, 0.0058, 0.0173)	…	(0.0013, 0.0005, 0.0002)
I_{10}	(0.0192, 0.0833, 0.1345)	(0.0038, 0.0007, 0.0004)	(0.0058, 0.0096, 0.0289)	…	(0.0013, 0.0002, 0.0001)
I_{11}	(0.0192, 0.1089, 0.1729)	(0.0038, 0.0008, 0.0004)	(0.0058, 0.0135, 0.0289)	…	(0.0013, 0.0003, 0.0002)
I_{12}	(0.0192, 0.0833, 0.1729)	(0.0038, 0.0008, 0.0004)	(0.0058, 0.0135, 0.0289)	…	(0.0004, 0.0002, 0.0001)

- the achievement of sustainable development goals in the operation of transport systems and supply chains is achieved by bringing the goals, methods and principles of green logistics into conformity with the goals and objectives of the organization's economic activity;

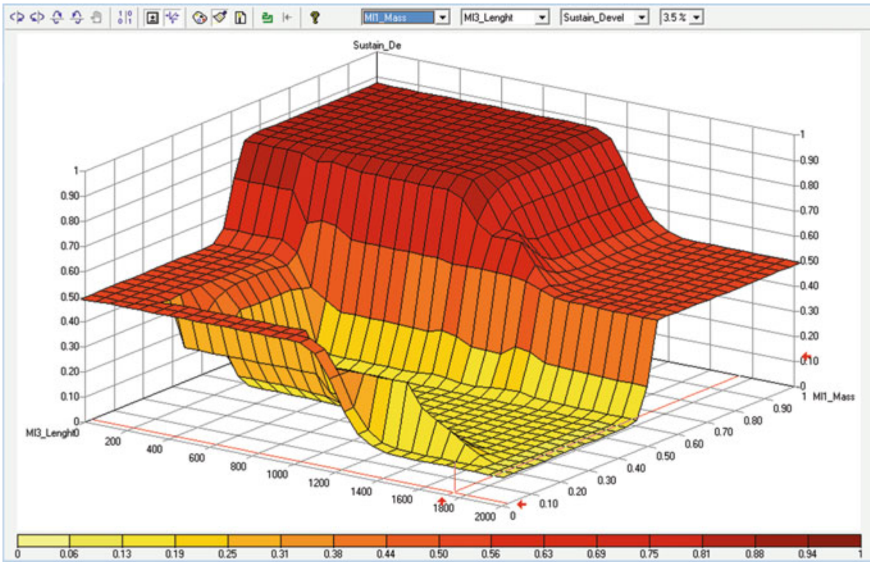
Table 28 Closeness coefficient (CC_i) and final ranking of green logistics instruments

Instrument name	d*	d−	*CCi*	Rank
Use of environmentally friendly modes of transport (I_1)	0.33340	0.24577	0.42435	9
Use of intermodal technologies and multimodal transport (I_2)	0.21181	0.35647	0.62728	2
Use of vehicles with the least environmental impact (I_3)	0.35483	0.23381	0.39721	10
Choosing a vehicle with a higher carrying capacity (cargo capacity) (I_4)	0.30776	0.28637	0.48199	7
The use of environmentally friendly fuels and lubricants (fuels) (I_5)	0.45339	0.09608	0.17487	12
Ensuring technological unity of the transport and storage process (I_6)	0.19521	0.41659	0.68092	1
Vehicle route optimization (I_7)	0.26767	0.33436	0.55539	5
Vehicle speed optimization (I_8)	0.23209	0.35363	0.60375	3
Eco driving (I_9)	0.37680	0.19040	0.33568	11
Consolidation of cargo flows in the directions (I_{10})	0.31117	0.26853	0.46321	8
Optimization of cargo flow structure (I_{11})	0.24126	0.36324	0.60089	4
Operational management of material flow parameters to ensure uniform loading of transport infrastructure elements, reduce congestion and inventory (I_{12})	0.28198	0.30005	0.51553	6

Table 29 Input data for modeling green supply chain flows

Indicators and parameters of logistics flows	Actual values of indicators and parameters (I_k)
Flow controllability coefficient	0.8
Flow irregularity coefficient	1.1
The complexity factor of the flow structure	0.9
Discrete flow rate	0.9
Flow differentiability coefficient	1.0
Flow mass, t	200
The flow rate, km/day	400
The length of the flow route, km	1850
Integral indicator of supply chain sustainability	0.125 (low)

(a) Mass – Route length –Sustainability



(b) Speed – Route Length – Sustainability

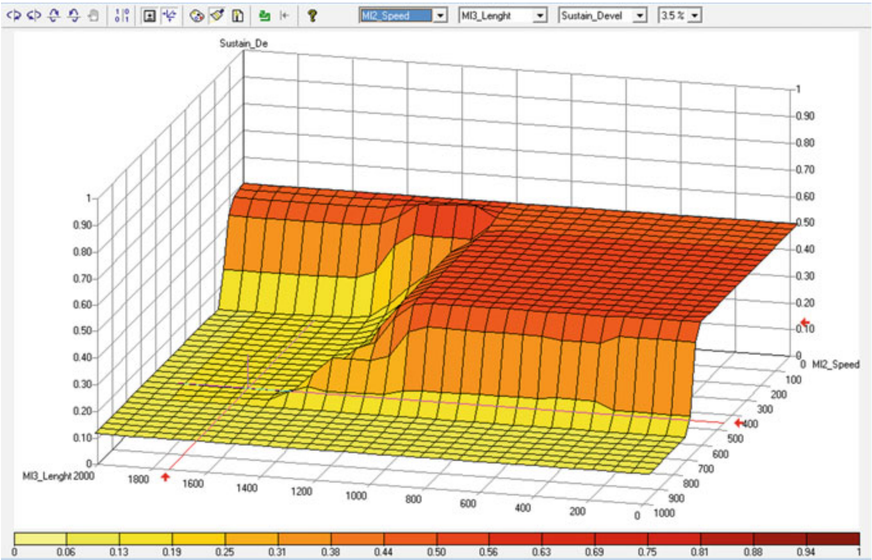


Fig. 18 Supply chain sustainability assessment results (on the example of the carriage of goods by road along the route Moscow-Yekaterinburg)

(c) Mass – Speed – Sustainability

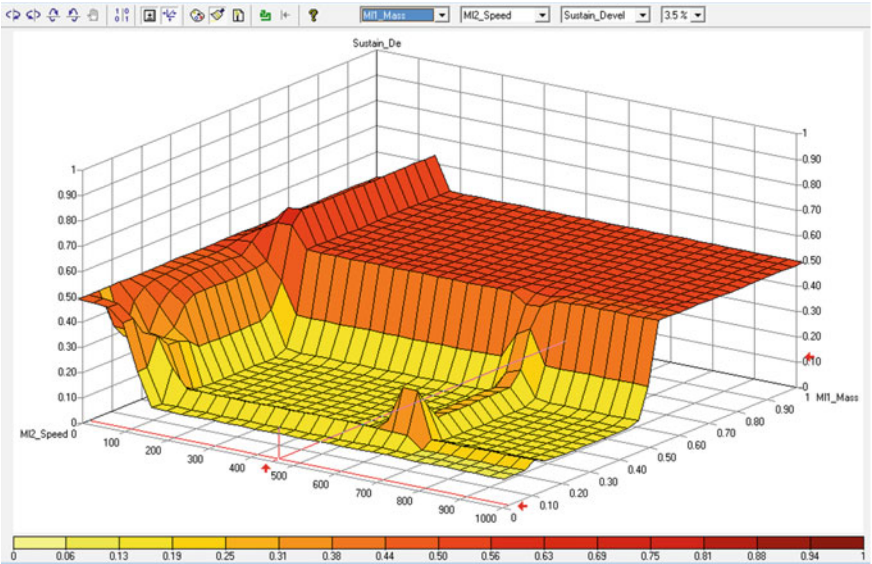


Fig. 18 (continued)

Table 30 Green supply chain flow simulation results

Fuzzy inference model variable	Actual values (I_k)	Simulation options using green logistics instrument			
		Speed optimization (I_8)	Route optimization (I_7)	Use of a vehicle with a higher carrying capacity (I_4)	The use of environmentally friendly modes of transport (I_1)
Instrument rank	–	3	5	7	9
Discrete flow rate	0.1	0.1	0.1	0.4	0.9
Flow mass, t	200	200	200	200	200
The flow rate, km/day	400	550	450	400	270
The length of the flow route, km	1850	1850	1793	1850	1764
Supply chain sustainability	0.125	0.307	0.1357	0.1391	0.4027

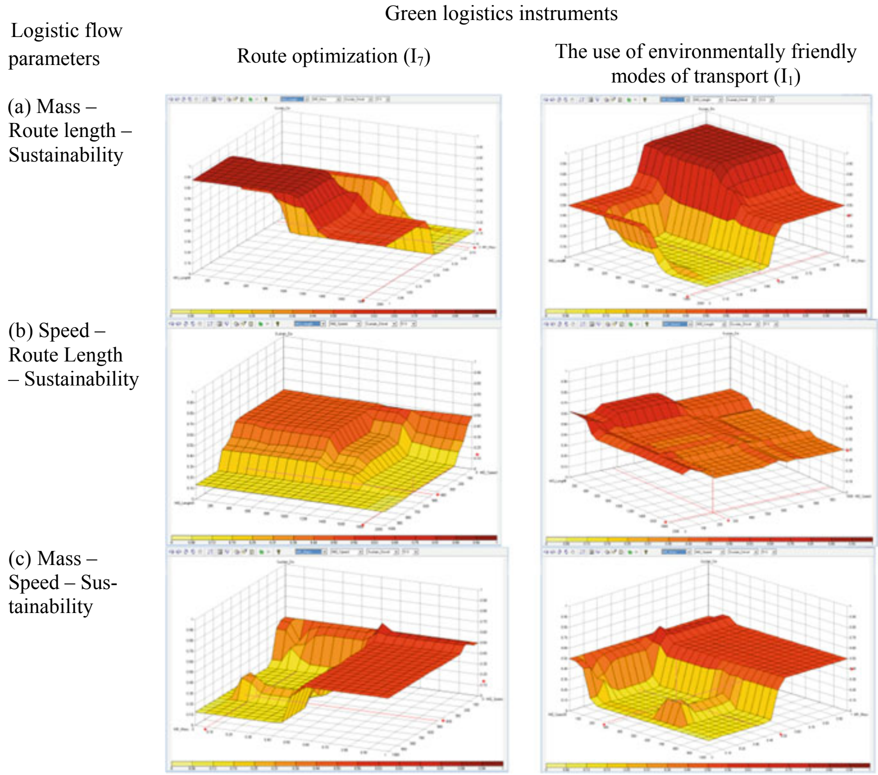


Fig. 19 Supply chain sustainability assessment results using green logistics instruments I_7 and I_1

- the formation and development of transport systems and supply chains is based on the use of the system of principles of green logistics, which is a synthesis of the principles of sustainable development with logistic principles;
- achieving and maintaining a balance between the economic, environmental and social sustainability of the transport system is ensured by the implementation of the developed system of methods and instruments of green logistics, affecting elements of the logistics system and logistics flows.

Assessment of logistic flows in green supply chains is carried out using the original system of parameters and indicators of logistic flows, which includes the following groups of indicators: economic indicators, energy and environmental indicators, quality indicators, statistical indicators. The main controlled flow parameters are: mass flow; flow rate; length of the flow route.

The proposed methodology for managing flow parameters in green supply chains includes the following main steps:

1. Identification of parameters and indicators of logistics flows. The choice of green logistics instruments and the ranking of selected instruments by the degree of

influence on the performance of logistics flows using the fuzzy AHP-TOPSIS method.
2. Building a fuzzy model of logistics flows in green supply chains using the fuzzyTECH program. The inclusion in the fuzzy model of the actual values of the parameters and indicators to assess the sustainability of the supply chain.
3. The selection and implementation of a green logistics instrument to increase the sustainability of the supply chain and bring the parameters of logistics flows in line with sustainable development goals.

Using the proposed approach to managing the parameters of logistics flows in green supply chains will improve: the quality of the assessment of the status of logistics flows according to the criterion of compliance with the goals of the concept of sustainable development; the effectiveness of decision-making on flow management in the logistics system based on the use of a system of methods and instruments of green logistics.

Further development of the developed methodology will be carried out in the following areas:

- clarification of the developed fuzzy rules and the interdependence of indicators and parameters of logistics flows based on simulation of supply chains;
- development of a method for checking the correctness of the choice of an instrument for influencing the parameters of logistic flows (green logistic instrument) and evaluating the effectiveness of its implementation;
- development of a method for teaching the model of fuzzy inference by combining it with a simulation model of supply chains;
- development of a method for choosing the optimal sequence of implementation of green logistics instruments based on forecasts of changes in parameters and indicators of logistics flows obtained using simulation of supply chains.

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The Paradigm of Sustainable Transport and Mobility in Modern Transport Policy—A Case Study of the Mobility of the Creative Class in Poland

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Abstract This chapter is dedicated to the problems of sustainable urban mobility. Sustainable urban mobility is the basic instrument for improving the quality of urban natural environment by reducing the emission of air pollutants, noise and consumption of non-renewable natural resources by transport. In this paper, the authors present their observations concerning the paradigm of sustainable development in the formation of urban mobility based on the research on mobility preferences and behaviours of representatives of the creative class carried out at the University of Economics in Katowice. First of all, the paper presents issues related to the essence of the paradigm of sustainable urban mobility, particularly in terms of its inclusiveness. The existing literature on the relationships between the development level of urbanised areas and mobility was also reviewed. Furthermore, the legal acts of the European Union concerning the mobility policy framework were inventoried and characterised. The purpose of the article is to identify and analyse the transport behaviours and postulates of representatives of the so-called creative class in Poland. The paper presents the results of surveys conducted in three Polish metropolitan areas, in the total group of 450 creative sector workers.

Keywords Sustainable urban mobility · Public transport · Polish metropolitan areas

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1 Sustaining Urban Mobility as Instrument for Environment Protection

Not only does urban mobility determine individual freedom in the urban space, but it is mostly of key importance for the social and economic urban development. One of the paradigms of urban mobility is sustainable development, which is the foundation of modern transport policy. Sustainable mobility refers to effective management of non-renewable environmental resources—in cities, and particularly in metropolises, transport is one of the biggest sources of natural environment pollution, especially air pollution (smog) and noise. Sustaining urban mobility is an important instrument for efficient and effective natural environment protection, not only in cities, but also in their surroundings. We should also emphasize that this is not only related to nature, but mostly to human life environment. Apart from investigating the development factors, modern economic sciences search for the principles of effective and socially acceptable distribution of goods and services, both now and in the future. Due to the coincidence in time and research subject of the problems of sustainable and inclusive development, these problems are regarded collectively, or even as synonyms. The question is how to distribute the growth effects—now and in the future, as well as how to exploit non-renewable resources and rare goods, taking into consideration the future generations and their needs, which is the research subject of the prescriptive trend of environmental economy, which is referred to as green economy.

In this paper, the authors have presented their observations concerning the paradigm of sustainable development in the formation of urban mobility based on the research on mobility preferences and behaviours of representatives of the creative class carried out at the University of Economics in Katowice. Creative class, as defined by R. Florida, is a growing social group, responsible for progress and innovative development of cities, which are regarded as the centres of growth [1]. Not only does creative class lay foundations for this growth, but it also performs an important opinion-making function, and in particular, it creates the pattern of mobility behaviours. That was the basic premise for choosing this social group as the subject of our research interest. The empirical studies were carried out in three largest metropolises in Poland. In these agglomerations, similarly as in the whole country, there are currently dynamic changes related to building social capital, and the mobility preferences and behaviours are particularly changing.

The purpose of the research project whose results are presented in this paper was to examine the relationships between sustainability and inclusiveness of mobility, as well as to assess the impact of these processes on urban development. On the other hand, the empirical purpose was to assess the risk excluding the functioning of instruments for sustaining urban mobility used in transport policy. Verification of the correctness of research assumptions was based on the review of the literature on the subject (especially concerning the significance of sustainable mobility paradigm in transport policy) and on the study of initial mobility preferences and behaviours of the creative class in three largest agglomerations in Poland—the research was carried out by means of a survey questionnaire conducted by a professional research centre.

Moreover, the research was based on the experience gained during the implementation of scientific work, as well as on research and development work in the field of urban mobility.

The paper presents the analysis of the essence and basic tools for sustaining mobility in the cities. In particular, tools such as electromobility and personal transport were described. The significance of sustainable development in the European transport policy was presented. However, the most important problem is the assessment of conclusions drawn from the research on the mobility preferences and behaviours of the creative class.

The practical importance of mobility administration and management means that these issues are and will be developed in the application research. However, it should be noted that mobility, particularly in the environments that are in many aspects as complex as metropolises, are still a very little known research area in many scientific disciplines. Due to this fact, the undertaken research shall be regarded as a contribution to the development of a new scientific subdiscipline of great empirical significance, i.e. mobility economy. The transport system has a direct influence on the quality of life in the city. Transport must meet the growing expectations and adapt to the changing circumstances, including the increasing number of urban population, growth of individual car transport (especially in Poland), ageing society, change of economic structure (departure from heavy industry towards modern services), as well as increasingly high ecological requirements. The concept of planning transport by modelling mobility is connected with the creation of such a system of movement in the urban area that, on the one hand, will increase the availability of specific areas and services, being a significant stimulus for development, and on the other hand, will contribute to improving both the quality of life of inhabitants and the condition of the natural environment. Infrastructure and modes of transport are regarded as tools for facilitating movement rather than as an element creating mobility. The idea of planning mobility results e.g. from the fact that high economic and social costs of construction of transport infrastructure frequently prove to be ineffective. The expansion of road infrastructure in order to increase the capacity and reduce congestion often turn out to be a short-term solution.

2 The Essence of Sustainable Mobility Paradigm

2.1 Evolution of the Sustainable Mobility Concept

Sustainable development is defined in different ways, often broadly. Such is the case of the definition provided by J. R. and J. G. Engel, who, considering the problem of development in terms of ethics, perceive sustainable development as human activity maintaining and preserving the foundations of life on Earth [2]. Such an extended approach raises certain doubts, because the nature had been developing for billions of years, while at the same time the fate of entire species (not to mention their individual representatives) was of little importance [3]. Taking into consideration the broad use and application of the concept of sustainable development not only in science and journalism, but also in legal norms (including at the constitutional level), a precise and unambiguous approach was advisable.

The discussion about sustainable development is a continuation of the reflections on corporate social responsibility. The importance of corporate social responsibility and sustainable development is based on the exposure of external effects and costs of business activity. In particular, external costs may lead to the exclusion of defined consumer groups from the distribution of goods and services.

The subject matter of corporate social responsibility was developed in the second half of the 20th century, although its origins could be traced back to the initial stage of capitalism development. The problems of business ethics and responsibility were the subject of "Rerum novarum" encyclical issued by Pope Leo XIII in 1891. From the perspective of the relationships between business and its surroundings, the key problem is to determine the non-economic role and goals of both the company and the entrepreneur. M. Friedman explicitly claims that the role of business is to maximise profits, whereas social issues are the responsibility of the state. Friedman formulated this opinion already in 1970, in the article with the explicit title "The Social Responsibility of Business is to Increase its Profits" published in The New York Times. According to Friedman, the entrepreneurs, and especially the managers calling for corporate social responsibility act contrary to the goals of the company, as well as against the company owners; what is more, by assigning funds to activities related to social responsibility, they may cause an increase of prices, and therefore, act to the detriment of customers. Nowadays, Friedman's views are in retreat. Were they not, however, based on a misunderstanding? Profit-making may and should be consistent with the respect for ethics, and Friedman does not question it. Moreover, the social activity of a company can be closely related to the economic goals. It may be intended to improve such profit factors as image building (which may impact not only an increase of the brand value, but also the so-called employer branding, which increases the effectiveness of employment), or improvement of efficiency (thanks to a greater employee identification with the company).

The development of the corporate social responsibility concept influenced the business practice and expansion of the circle of business activity stakeholders. These issues became an object of interest for the state, which was forced to address the questions about the costs of growth and the way the effects of the growth are to be consumed. That was the beginning of formulation of the sustainable development concept. The starting point was the problem of limitation and non-renewability of natural resources. The forecasted exhaustion of resources and environmental pollution forced government reactions and cooperation in the field of environmental protection and replacement of non-renewable resources with renewable resources. That was the beginning of the paradigm of sustainable development, i.e. such development that allows to increase the welfare, while at the same time reducing the consumption of non-renewable resources, especially including the natural environment. Sustainable development is regarded as the most socially effective (taking into consideration the external costs), and in particular, it does not affect the needs of future generations. This last aspect makes sustainable development inclusive in inter-generational relations.

The notions of corporate business responsibility, sustainable and inclusive development address the problems of business ethics and civilisation development, as well as such fundamental issues as the right of individuals to consumption and freedom. These terms are not synonyms. While CSR means business (i.e. supply potential) which is ethical and takes into account the values which drive the society, the precise meaning of sustainable development is the protection of non-renewable resources (and more broadly speaking, the social effectiveness of production, after including the external costs). On the other hand, inclusiveness is nothing but fair distribution (satisfying the demand). An example could be the introduction of restrictions in access to the urban space for traditional cars, which means the exclusion of the owners of such cars, to the benefit of richer people who can afford to buy electric cars. Therefore, sustainable development, socially responsible and inclusive, should be regarded as a complementary concept of development, which takes into account both negative effects and external costs, as well as the importance of ethics in business and respect for all citizens.

In Poland, sustainable development is included in Art. 5 of the Polish Constitution ("The Republic of Poland shall safeguard the independence and integrity of its territory and ensure the freedoms and rights of persons and citizens, the security of the citizens, safeguard the national heritage and shall ensure the protection of the natural environment pursuant to the principles of sustainable development". [4]). Art. 5 of the Constitution indicates that sustainable development refers to activities which are connected with the environmental protection. The Environmental Protection Law of 27 April 2001 defines sustainable development as "socio-economic development which integrates political, economic and social actions, while preserving the natural equilibrium and the sustainability of basic natural processes, with the aim of guaranteeing the ability of individual communities or citizens both in the present and future generations, to satisfy their basic needs" [5]. Despite its expanded nature, this definition is also consistent with the framework defined by UN (Bruntland Report of 1987: "in essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations" [6]). It should be noted that both in Polish legislation and in Bruntland Report, the essence of sustainable development is economic growth as a factor that enables progress and fight against poverty. This view of sustainable development was also maintained in the documents approved at the UN Climate Change Conference in Rio de Janeiro in 1992 and in the initiatives that were launched following this breakthrough climate conference [7].

With reference to transport and mobility, the sustainable development concept resulted in models and tools for sustaining urban transport and mobility. Zero emission transport can be considered as sustainable, because it provides the possibility to fulfil mobility needs of future generations. However, the concept of zero emission should be regarded broadly: if it is electric transport, the energy should come from renewable sources. Sail-driven water transport and bike transport (with the exception of power assisted bikes, unless the energy comes from renewable sources) can also be considered as zero emission transport. Zero footprint defined in this way is currently of marginal importance in fulfilling transport needs and mobility. The use of electric drives in the case of fossil-fuel or nuclear-generated energy only provides local zero footprint, although the environmental effectiveness of traditional and nuclear power plants is constantly growing. Sustainable mobility means such a model of transport behaviours (also referred to as mobility behaviours) where transport needs are fulfilled either by means of zero emission and low-carbon transport, or by walking.

2.2 Social Context of Mobility

Urbanisation as a global process leads to increasing the volume of transport needs, as well as to a higher structural complexity of such needs. In the case of large cities, and especially metropolises, transport systems are not capable of fulfilling the transport demand smoothly and effectively, especially during the peak hours. The spatial and infrastructural limitations cause congestion, whereas the widespread use of combustion cars is one of the reasons behind the formation of urban smog, which has a negative impact on human health. Scientific research shows the impact of smog on mortality and occurrence of various diseases. WHO attributes 26,000 deaths in Poland per year to the exposure to particulate pollutants (according to cautious estimates from 2012). The negative impact of pollution has been proven especially as regards its effect on the respiratory system (bronchial asthma—there are approximately 4 million asthmatics in Poland, chronic obstructive pulmonary disease (COPD)—approximately 2 million people, respiratory infections). Air pollution also increases the number of cancer diseases, especially the lung cancer. Moreover, research shows the negative influence of air pollution on cardiovascular diseases—including in particular thromboembolic complications, cardiac arrhythmias, ischemic heart disease and cardiac failure, atherosclerosis and heart strokes. A statistically significant relationship with air pollution has also been found in the occurrence of central nervous system diseases [8].

Managing mobility, and especially sustaining mobility, is the key area of modern urban policy. These issues have increasingly become an object of domestic and international policy, rather than only transport policy. The following can be mentioned among the derivative and related aspects of sustainable mobility policy: energy policy (including the problem of energy security), industrial policy and spatial development. The growing importance of urban mobility, which is becoming a bottleneck for development in metropolitan areas, is also evidenced by the increasingly intense discussion in traditional and social media, which concerns not only the attractiveness and originality of new mobility forms (e.g. as part of the so-called collaborative consumption, referred to as co-sharing economy), but also their connection with sustainable development (including effectiveness). Non-profit organizations, politicians, and increasingly often inhabitants participate in this discussion as well.

Sustainable mobility can be achieved by means of various tools. It is usually recommended to use such tools in a complex manner and adjust them to the local conditions [9]. However, searching for simplified solutions or shortcuts happens in some cases, with the use of instruments that have just become trendy and catchy for the media (frequently referred to as 'modern' in an evaluative manner), and then in transport policy practice, which, unfortunately, is also transferred to scientific discussions. The modern media communication is characterised by high simplification, dynamics and often exaggeration, intended to attract the readers' attention, which leads to attempts to expose a limited pallet of instruments as sufficient in order to achieve the expected results. In particular, this applies to the instruments that are not either restrictive or exclusive in nature. However, a closer analysis shows that a restriction usually takes place, but rather indirectly than directly (e.g. free urban transport causes a significant increase of demand, which may lead to restrictions in access to modes of transport, including for people with disabilities, who may find it more difficult to get into a crowded vehicle).

Historically, urban mobility was based on pedestrian traffic. With the growing urbanisation and increasing size of cities, new methods of fulfilling mobility needs appeared. Currently, increasing attention is paid to the necessity of priority treatment of pedestrian mobility [10] by eliminating car transport (especially combustion cars) to the benefit of pedestrian traffic in cities or selected zones in cities [11], or planning the spatial development of a city in such a manner that all needs could be fulfilled within the pedestrian traffic range [12]. In particular, this means establishing workplaces and residential areas in close proximity. And here the question of inclusiveness arises, which is connected with the value of land and real property in the cities. Both the areas intended for commercial activity and housing in cities are characterised by a relatively high value in comparison with non-urban areas, especially in the very city centres. When it comes to residential housing, it frequently takes the form of apartment buildings, whose price often reaches extreme values. For example, the price of 1 m^2 in an apartment building in downtown Warsaw exceeds EUR 5774 [13]. High prices are also characteristic for the locations near metro stations [14]. In relation to income, flats in agglomerations, including especially in Warsaw and Kraków, are characterised by the lowest accessibility (Table 1).

High housing purchase and rental prices in prestigious locations are acceptable for people with high income. The owners of such flats are managers and specialists employed in prestigious locations situated in the city centre. From this perspective, "city for pedestrians" becomes a "city for the rich". In the "city for pedestrians" concept, the employees, officers, students and pupils that are essential for the functioning of a city should reach their destination by public transport. This means closing the city, or at least its centre, to vehicle traffic. Similarly selected districts may also be closed to vehicle traffic and become pedestrian zones, connected with the city centre by means of metro or intercity rail stations.

Is the concept of a city for pedestrians seen in this way not an idea of a city with restricted availability, where the preferred mobility model takes into consideration mostly individuals with relatively high income? If so, then this is the concept of a non-inclusive city, even if it appears to be sustainable. In this way, it begins to

Table 1 Prices and relations between prices of flats and income (December 2018, EUR 1 = PLN 4.33)

	Warsaw	Kraków	Wrocław	Poznań
Average remuneration (EUR)[a]	1490.41	1307.16	1253.60	1352.13
Prices of flats on the primary market (EUR/m^2)[b]	1976.96	1597.03	1558.89	1582.63
Prices of flats on the secondary market (EUR/m^2)[b]	1888.08	1529.06	1422.40	1309.07
Number of m^2 of a flat on the primary market for average remuneration	0.75	0.82	0.8	0.85
Number of m^2 of a flat on the secondary market for average remuneration	0.79	0.85	0.88	1.03

[a]Average gross remuneration in the company sector in December 2018
[b]Transaction prices of flats according to the National Bank of Poland in the third quarter of 2018
Source [15]

resemble the ancient and medieval times, when living in a city was the privilege available only for higher and richer classes. At the same time, the city development was or was supposed to be orderly, as evidenced by the search for an ideal city where spatial development was subordinated to ideas and functionality [16].

Modern city is an available and attractive area. In European cities, suburbs originated as an area of voluntary exodus for the inhabitants of city centres and are not synonymous with poverty zones inhabited by precariat (unlike cities in the developing countries that frequently locate the poorer in destitute suburbs, i.e. slums, by introducing high material entry barriers). The origin of urban areas inhabited by precariat and poorer population is a combination of multiple factors (especially poor immigrant assimilation). Polish cities are characterised by the dispersion of poverty zones [17]. However, this situation will be changing—the increasingly intense development of city centres with office buildings and accompanying hotels, shopping centres and residential buildings will lead to an increase of the real property value in the centres of metropolises; therefore, residential buildings will be replaced by utility buildings and high-standard (and high-price) residential buildings. Therefore, the risk of mobility exclusion for people with lower income seems to be quite real.

A significant role in fulfilling mobility needs and sustaining mobility is played by public transport, which allowed for quick development of urbanisation thanks to its mass character. Public transport was the first mass urban transport handling system. It was not until the second half of the 20th century that its percentage was significantly reduced by the substitute individual car transport. The downward trends of the share of public transport in fulfilling transport needs are currently stagnating—especially in metropolises, where mobility cannot be effectively supported by a less efficient car transport system and where the share of public transport in fulfilling transport needs even begins to grow. The development of public transport and increase of its availability (in terms of space, time and costs) definitely influenced the reduction of mobility exclusion in modern cities. Car, with all its flaws, is characterised by even higher availability, which is why it began to replace public transport as the substitute. A special feature of public transport is the low specific greenhouse gas emission (per passenger), particularly in the case of a metropolis with a large share of rail transport, which is based on electric propulsions. Moreover, it is worth noting that the current standard in traditional combustion engines in buses is to comply with very high exhaust emission standards (combustion vehicles increasingly often have Euro 6 standard, which means, in the case of diesel engines, not only a lower emission of carbon dioxide, but also of nitrogen oxides). Therefore, especially in large cities and metropolises, public transport should be considered as the basic mobility management tool.

2.3 Electromobility in Fulfilling Transport Needs in Cities

Sustaining urban mobility is based on a broad use of public transport, as well as bike and pedestrian traffic. These issues have already been discussed in detail earlier. The above-mentioned instruments can be referred to as classic or traditional. Currently, the following instruments (referred to as modern) are considered to be particularly promising from the perspective of sustainable mobility:

- electromobility,
- sharing modes of transport,
- personal transport (scooters, boards, roller skates).

Urban electromobility concerns both traditional transport subsystems in the city (individual car transport, two-wheel transport and public transport), as well as new transport subsystems, such as personal transport and systems of shared car transport (car sharing), as well as two-wheel transport (bike sharing and shared scooters). Therefore, the following transport systems in which electromobility appears can be distinguished:

- public transport using electric vehicles,
- individual electric cars,
- private electric bikes and scooters,
- electric car sharing,
- electric bike sharing and shared electric scooters,
- electric means of personal transport (scooters, boards).

Treating electromobility as the foundation of the current and future mobility model is rooted in the policy of decarbonising transport and logistics. However, it has been emphasized in the literature on the subject that it currently does not have to be the most effective instrument of decarbonisation (taking into account the external costs) [18]. The so-called green technologies also generate external costs, which are difficult to estimate precisely e.g. as a result of non-market calculation methods [19]. However, the development of technology for obtaining electricity from renewable sources (particularly solar energy) allows to predict the long-term and significant reduction of own costs related to electromobility, which will not only change the own costs of electric cars, but especially the balance of external costs.

The competitive position of electromobility also depends on the development of traditional propulsions. Combustion engines are characterised by the reserves of efficiency improvement and their environmental effectiveness grows on a regular basis. It should also be remembered that electromobility either reduces to a low extent, or does not reduce at all certain external costs—namely congestion, land consumption and costs of accidents. The cost competitiveness of electric propulsions in road transport is mainly influenced by the following factors (apart from the own costs and external costs of electricity):

- significantly higher price of electric buses,
- investment expenditure on the development of charging technology and necessity of expensive replacement of batteries,
- lower efficiency caused by the necessity to charge batteries.

Electric buses locally allow to obtain significant ecological effects. However, the inclusion of all conditions in the balance shows that the global (domestic) effect of replacing buses with traditional propulsions by electric buses can be unfavourable. This has been observed in the comparative analysis of the replacement of the rolling stock operated in Sopot. In the perspective of 25 years, even when taking into account the reduction of external costs (additionally based on assumptions which are not verified by the market)—electromobility is only beneficial at a local scale, whereas on the national level, the "diesel" variant assuming the replacement of rolling stock is over 14% more favourable [20]. On the national level, due to the structure of electricity production, the electromobility options considered are less beneficial not only comprehensively, but also in terms of external effects.

Electric cars are also apparently considered as an exceptionally effective tool for sustaining urban mobility. However, it shall be noted that electric car:

- does not eliminate congestion,
- does not improve safety in road traffic (and if so, this is thanks to the application of telematic solutions, which are also installed in combustion vehicles),
- has a smaller range (requires charging), which may not be an obstacle in the city, but may create barriers reducing the availability in case of suburban journeys,
- is twice more expensive than gasoline vehicles, which is reflected e.g. in the sales of such cars—only 637 electric cars were registered in Poland in 2018 [21] (the target 1 million electric cars by 2025 assumed by the government seems to be completely unreal).

Many countries use preferences for the buyers and holders of electric cars. In Norway, an electric car buyer is exempt from 25% VAT, and moreover, pays 50% of road tolls and is exempt from the road tax, which has been criticised—the Danish climate minister noted that this is the most expensive instrument of climate policy, which can only be applied thanks to Norway's revenue from the extraction of oil [22]. In Poland, there are also subsidies for the buyers of electric cars [23] and preferences related to access to city centres (exemptions from parking fees). This means access preferences for those who can afford to buy an expensive car (despite the announced discounts, such vehicle will be significantly more expensive than a new combustion vehicle—not to mention a second-hand car—and its availability will be limited to people with a higher than average income [24]). Access preferences in the city for such vehicles mean that the availability of urban space for the owners of cheaper vehicles is reduced.

2.4 The Role of Bike in Shaping Mobility

Bike is regarded as an important element of sustainable urban transport and sustainable mobility model. This is not only because of zero footprint, but also due to its positive impact on health [25]. The European Cyclists' Federation estimates the annual "bike" benefits of UE-28 (taking into account the external costs) at the level of more than EUR 513 billion [26], out of which approximately EUR 191 billion is the effect of positive impact of bike mobility on health. For this reason, bike, together with pedestrian mobility and movement by means of boards, scooters, wheelchairs and ski desks, are considered to be elements of the so-called active mobility or active transport—this term refers to human-powered modes of transport, whereas electrically powered modes of transport (e.g. scooters) are regarded as examples of hybrid transport [27]. Active mobility and hybrid mobility inevitably bring significant health lifestyle changing benefits, and consequently become a factor in building social capital of modern metropolises. The advantages of active mobility must be regarded precisely in this context and cannot be perceived as a full alternative to cars—such an alternative, particularly in the Polish spatial, climatic and cultural conditions, is offered by public transport. Bike as a mode of transport also means healthy lifestyle, tailored to the so-called development trends of leisure industries. The development of bike infrastructure, bike sharing system, as well as common interest in bikes and healthy lifestyle are particularly important for the society [28] (Fig. 1).

The share of bikes in fulfilling mobility has increased in many cities. These are mainly private bikes, however, the importance of public bikes available in the form of collaborative consumption (bike sharing) grows relatively dynamically, especially in the area of large cities. The share of bikes in fulfilling transport needs in European cities is not higher than between a few and several per cent (with the exception of Scandinavian and Dutch cities—Table 2). It seems that spatial factors are a sort of "glass ceiling" for the increase of this ratio, i.e. travel distance and time, which are usually stated as the causes of withdrawal from the use of car in urban travel, apart from the climate issues [29]). Therefore, bikes, especially in the bike sharing formula, should be regarded as the so-called "last mile" mode of transport—bikes should increase the availability of public transport (mainly including rail transport). Therefore, smooth operation of this type of bike transfer systems by the operators between parking stations is required, so as to ensure the availability of bikes.

Bike should be treated as a complementary system to public transport—however, research concerning the effect of introducing free fare public transport [31] shows that these two systems are substitutional [32]. What is more, it turns out that bike as a way to fulfil mobility needs is selected, to a large extent, for income-related

Table 2 Share of bike in fulfilling mobility in cities

EU capitals	Share of bike (%)	Research year
Copenhagen	35	2010
Amsterdam	32	2012
Berlin	13	2008
Ljubljana	12	2013
Helsinki	11	2013
Zagreb	10.1	2012
Stockholm	9	2013
Dublin	7.9	2013
Vienna	6	2013
Riga	4	2014
Brussels	3.5	2013
Luxembourg	3.5	2011
Sofia	3	2010
Nicosia	2	2010
Paris	2 (2nd source: 5%)	2013
Athens	2	2005
Budapest	2	2014
Bratislava	2	2012
London	2	2009
Prague	1	2013
Tallinn	1	2012
Vilnius	1	2010
Warsaw	1	2009
Lisbon	1	2013
Bucharest	1	2007
Rome	0.6	2012

Source [30]

reasons—in the Netherlands, as much as 30% of journeys made by 10% inhabitants with the lowest income are bike journeys (in the case of 10% of inhabitants with the highest income—it is as much as 20% of journeys) [33]. Seeking complementarity of bikes to public transport is a challenge not only for the bike sharing systems, but also for private bikes used in fulfilling mobility. The integration of transport in cities, including the creation of parking stations and bike stations, is a direction for reducing the substitutability of bikes in favour of their complementarity.

In the recent years, the so-called personal modes of transport—such as scooters and boards, often with electric propulsions, previously used for recreational purposes, have been in widespread use. The increasing interest in scooters is related to the development of collaborative consumption (sharing economy) [34]. In Poland, the

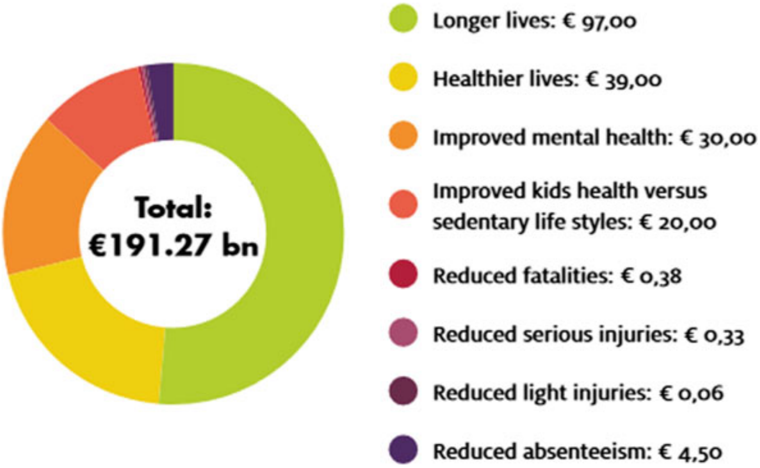

Fig. 1 Annual benefits of using bikes in terms of health improvement—estimates in EUR billion for EU 28 (data as of 2016). *Source* [25]

first scooters were offered for rental by the global start-up Lime in Wrocław (in the free floating model—i.e. the scooter can be left in any place) [35]. According to the estimates of "Rzeczpospolita", there are 3000 electric scooters for rental in 3 cities in Poland, and this number will increase to at least 12,000 over the next few months [36]. The market of shared vehicles (including also bikes, scooters and cars) is assessed to be strongly growing—the number of vehicles forecasted for 2019 is almost 37,000—although in terms of the number and income, the unquestionable leader is the bike (PLN 92.9 million, followed by cars at the level of PLN 57.2 million, scooters—PLN 15.7 million and scooters with approximately PLN 33.6 million) [37]. It should be emphasized here that the leader in the Polish bike sharing market obtains approximately 90% of income from urban subsidies and advertising. The adopted business model may turn out to be inefficient in the case of extending activity—this is what happened in the Tricity agglomeration (Gdańsk-Gdynia-Sopot), where the agreement with the system operator was terminated after 7 months of the operation of the metropolitan e-bike sharing system with over 1200 bikes (the main causes were attributed to the problems with bike dislocation and delays in the system extension) [38].

The enthusiasm related to the role of means of personal transport in sustaining mobility is discouraged by the following issues:

- the devices require electric power supply, which raises valid objections regarding the domestic effectiveness of their application in the case of energy mix based on non-renewable resources (similarly as in the above-quoted example of the planned investment in Sopot),
- the applicable legal regulations regard people moving by means of such vehicles as pedestrians, which does not allow them to use the roads for cars and bikes, and moreover, due to the fact that such devices can reach the speed of up to 40 km/h,

they constitute a significant threat for pedestrians (this also applies to electric bikes, in which an increase of speed may lead to more serious accidents [39]).

Personal means of urban transport, mainly offered in the collaborative consumption model, are regarded (especially by media) as an instrument that may quickly change the urban mobility model. There is no evidence proving such statements or data about the actual role of scooters in fulfilling mobility needs. It is also worth noting that this mode of transport poses risks for the pedestrian and bike movement (Fig. 2). Currently, high hopes for a change of mobility behaviours are placed on personal transport. The practice does not allow to form optimistic opinions. The operators have no control over the users' behaviours, which poses a serious hazard for pedestrians and cyclists. It is difficult to draw firm conclusions without research, but the hypothesis saying that personal modes of transport are substitutes of pedestrian movement, thus having no impact on sustaining transport and mobility in cities, seems to be probable.

Fig. 2 Examples of abandoned scooters rented in sharing-economy system (Siemianowice and Katowice, 2019)

3 Mobility in Transport Policy

3.1 Impact of the Development of Urbanised Areas on Mobility

Urbanisation understood as a social and cultural process expressed by the development of cities, increase of their number, growth of urban areas and share of urban population in the entire population (or share of population living in line with the urban patterns) [40] is one of the most characteristic global phenomena of the 20th and beginning of the 21st century [41]. Modern urbanised areas are most frequently multi-million cities, agglomerations and metropolises, characterised by a large concentration of population, as well as social and economic activity. The development of cities has a long history in which various factors have played a significant role, including such e.g.: geographical (convenient location), economic (industrial and service activity), political (centres of power), religious (places of religious cult), as well as social and cultural factors.

The modern philosophy behind the shaping of urban space was reflected in the New Athens Charter of 2003, also referred to as "the vision of cities of the 21st century" [42]:

1. The connected city: connecting through time—historical continuity.
2. Social connectivity—social balance, involvement, multi-cultural richness, connections between generations, social identity.
3. Economic connectivity—globalisation and regionalisation, competitive advantages, city networking, economic diversity.
4. Environmental connectivity—environmental balance, healthy city, nature, landscape, and open spaces.
5. Spatial synthesis—spatial linkages, connecting through character, continuity and quality of life.

Cities differ from one another in terms of the problems and expectations of their inhabitants. They also have different development conditions and opportunities due to the performed functions. Apart from the historically developed and constantly developing cities, there are also the so-called cities built "from the scratch", which are assumed to be modern cities of the future, ensuring an adequately high quality of life for their inhabitants. They are increasingly often referred to as "smart cities".

The concept of smart city as a modern city of the future assumes sustainable development of cities based on innovative technologies, which are applied in order to improve the functionality of cities in terms of management in a cost efficient, effective and ecological manner. Smart cities are defined in very different ways. There are frequently 6 basic components indicated as the elements of a smart city: smart governance, smart economy, smart mobility, smart environment, smart people and smart living [43]. Smart mobility as one of the elements of the smart city concept is vital in the functioning and development of the city, as well as the quality of life of inhabitants [44]. There are also development stages of smart cities (Smart City 1.0, 2.0, 3.0) [45].

It is generally considered that city can be regarded as “smart” when it undertakes investment in the human and social capital, as well as transport infrastructure for the purpose of active promotion of sustainable economic growth and high quality of life, including clever natural resource management, through participation of its citizens.

An interesting concept of the city according to Nijkamp [46] was presented by Lidia Mierzejewska [47] in her publication entitled *W poszukiwaniu nowych modeli rozwoju miasta*. The author writes that according to Nijkamp P., cities can be ranked from the smallest (XXS) to the largest (XXL), modelled on clothes in shops, adopting the quality of life of inhabitants as the criterion. According to this concept, dynamically developing, competitive and innovative contemporary cities can be defined as Self-Organising Innovative Complex Systems that should be characterised by [47]:

- dependence on creativity, innovation and management,
- high level of progress in the research and development area,
- productivity and competitiveness, which are decisive for the economic success,
- market orientation,
- development path defined by the evolutionary complexity and behavioural learning rules.

Following Nijkamp P., the author states that there are five basic factors that have an impact on the development of such cities and metropolitan areas (XXQ SIC), namely [47]:

1. economic capital—referring to the economic fundamentals that are necessary for the effective operation of the sustainable city area,
2. ecological resources—mainly concerning the environmental base, conditioning the sustainable development of the city,
3. technological systems,
4. geographical infrastructure,
5. social superstructure—represented by the social forces creating a sustainable society.

The quality of life (QoL) is an object of interest for many researchers in various scientific disciplines. It is a concept that inspired multiple studies over the last few decades and established its firm position in local, domestic and international programmes [48]. The assessment of the quality of life in cities (QoL) is currently a problem of growing importance, not only in the academic literature [49]. The issues that are objects of interest for the researchers also include air pollution, congestion and transport. The objective measurements or social indicators broadly represent the standard of individual living, covering verifiable conditions proper for a specific cultural unit [50].

Modern urbanisation is a highly complex and multi-aspect process, considered at several levels, e.g. in the demographic, social, economic, spatial, ecological and legal aspects [51]. The demographic aspect is the total urban population growth and increase of the urban population percentage, the economic aspect is the increase of the number and percentage of employees hired in sectors other than agriculture, the spatial aspect is the construction expansion and development of urbanised areas, whereas the social aspect is the popularisation of the urban lifestyle. The subject and stages of urbanisation are described in more detail by Daniela Szymańska and Jadwiga Biegańska in their publication entitled *Fenomen urbanizacji i procesy z nim związane* (The phenomenon of urbanization and related processes) [51].

Modern urbanisation processes, frequently referred to as metropolisation, have led to the occurrence of new spatial forms with an increasing urban-planning complexity [52]. An urban complex that is particularly huge in terms of population and space is referred to as a megalopolis, understood as a large urbanised area, formed as a result of territorial expansion of metropolitan areas that are geographically close [53].

As a result of the fast urbanisation process, in 2007 the global population became more urban than rural for the first time in history. It is expected that this process will be continued during the upcoming decades, and an increasing number of populations will be living in urban areas. Figure 3 presents the forecasted global urban population including more and less developed regions in 1950–2050.

Although it is expected that the global population will continue to urbanise, the urbanisation rate is predicted to slow down in the future. Due to this, it is expected that in 2018–2030 the global urban population will be increasing by 1.7% per year on the average, which is significantly less than in 1950–1970 (3.0%), 1970–1990 (2.6%), or in 1990–2018 (2.2%). It is also expected that the percentage of urban population will be growing at a slower rate: 0.7% in 2018–2030 and 0.6% in 2030–2050. Until

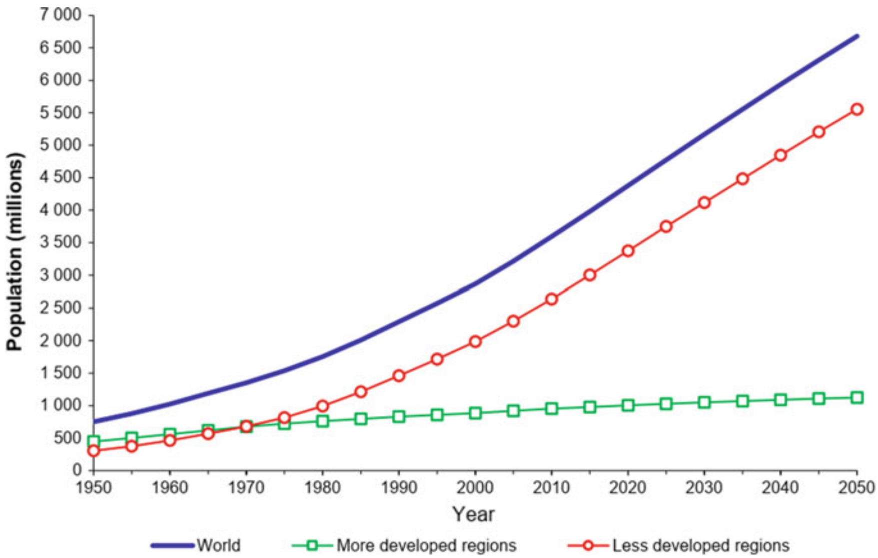

Fig. 3 Forecasted global urban population including more and less developed regions in 1950–2050. *Source* [54]

2050, it is expected that 68% of global population will be living in cities, whereas the number of inhabitants in cities will amount to 6.7 billion (Fig. 4).

Figure 5 presents forecasted global urban population including more and less developed regions in 1950–2050. Figure 6 presents global urban population including more and less developed regions in 1950–2050.

The data included in Fig. 5 show that the advantage of population in less developed areas will increase in comparison with the more developed areas. On the other hand, Fig. 6 indicates a clear disproportion between the urban population in more and less developed areas, as well as a significant forecasted increase of the urban population in less developed areas.

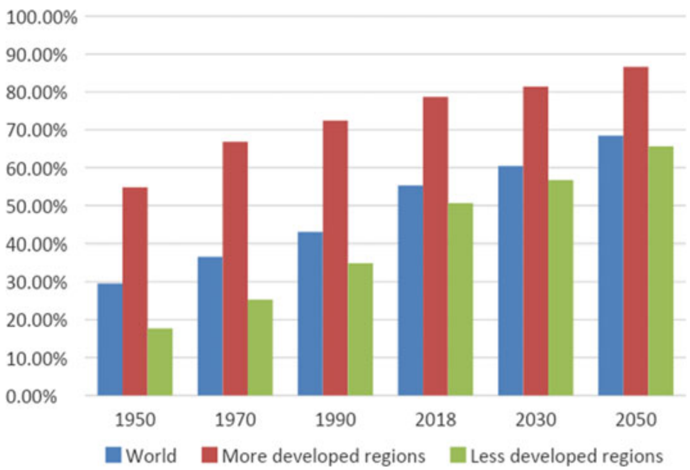

Fig. 4 Global urban population including more and less developed regions in 1950–2050. *Source* [54]

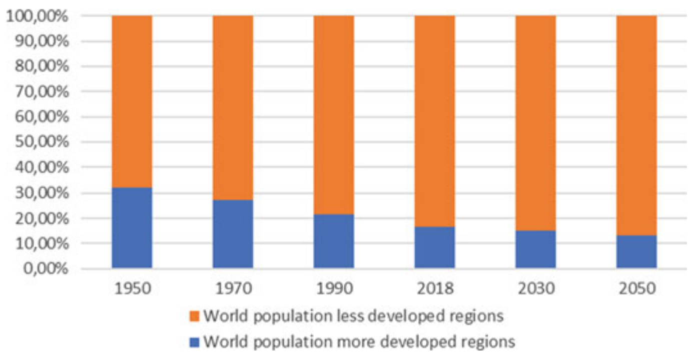

Fig. 5 Total global population including more and less developed regions in 1950–2050. *Source* [54]

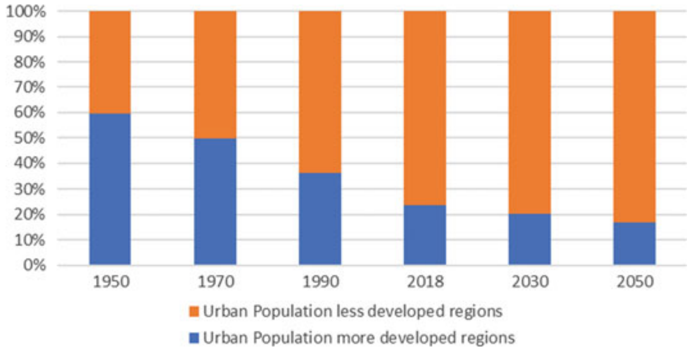

Fig. 6 Global urban population including more and less developed regions in 1950–2050. *Source* [54]

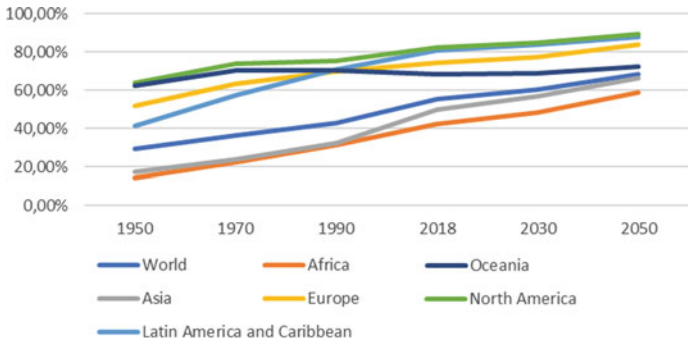

Fig. 7 Percentage share of global urban population by geographical regions in 1950–2020. *Source* [54]

Figure 7 presents the percentage share of global urban population by geographical regions in 1950–2020. As can be seen in Fig. 7, the increase of the number of population in urbanised areas is a general global trend. The highest urbanisation levels are achieved in highly developed countries. Until 2050, it is forecasted that the highest increase of urban population will take place in Africa and Asia.

Figure 8 presents the forecasted distribution of global urban population in 2050.

Urbanised areas do not develop at the same rate around the world. The fastest population growth is in the biggest cities—megacities with 10 million inhabitants or more. In 1970, 55 million people lived in megacities, whereas the biggest number of people lived in the cities with the population below 300,000 (730 million people). In 2018, the number of inhabitants in megacities increased ninefold to 529 million people, whereas in the cities with the population below 300,000, the number of people increased only 2.5 times, to 1.75 billion. Table 3 contains data concerning the number of inhabitants of cities divided into cities of various size in 1970–2030, as well as the percentage share of particular types of cities within urbanised areas.

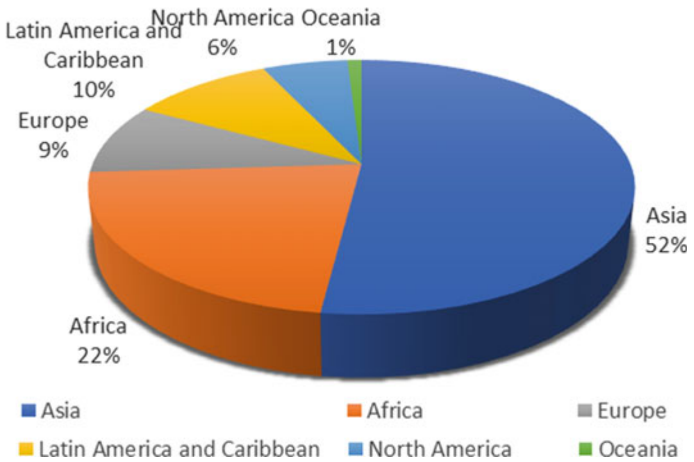

Fig. 8 Forecasted distribution of global urban population in 2050. *Source* Own study based on [54]

Table 3 Number of city inhabitants by city size in 1970, 1990, 2018 and 2030

City size (number of inhabitants)	Population (millions)				Percentage			
	1970	1990	2018	2030	1970	1990	2018	2030
Urbanised areas	1.354	2.290	4.220	5.267	36.6	43.0	55.3	60.4
10 million and more	55	153	529	752	1.5	2.9	6.9	8.8
5–10 million	107	156	325	448	2.9	2.9	4.3	5.2
1–5 million	244	467	926	1.183	6.6	8.8	12.1	13.8
500,000–1 million	131	208	415	494	3.5	3.9	5.4	5.8
300,000–500,000	87	159	275	320	2.3	3.0	3.6	3.7
Fewer than 300,000	730	1.147	1.750	1.971	19.7	21.5	22.9	23.1

Source [54]

It is forecasted that the number of inhabitants of megacities in 2030 will have increased to 752 million and will constitute 8.8% of the global population. Similarly, an increase of population is expected in cities of all other sizes. Currently, a majority of city inhabitants around the world live in cities with the population below 1 million. In 2018, two billion people lived in cities with less than 500,000 inhabitants and further 400 million people lived in cities with the population of 500,000–1 million inhabitants. It is forecasted that in 2030 still over half of the city inhabitants in the world (2.8 billion) will be living in cities with the population below 1 million. Compared to bigger cities, the cities with less than 1 million inhabitants are the most common type of cities in the world. It is predicted that the number of people living in cities of 500,000–1 million will increase from 415 million in 2018 to 494 million in 2030, which will constitute approximately 10% of the global urban population. One in five city inhabitants around the world lives in a medium-sized of 1–5 million

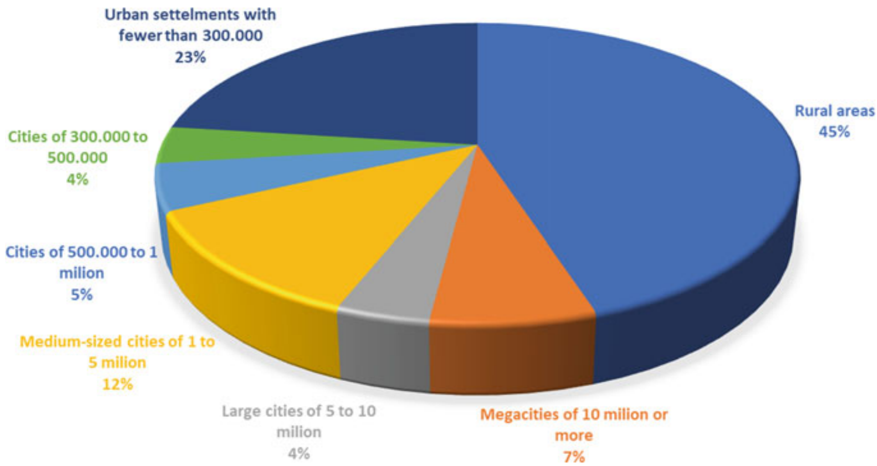

Fig. 9 Global population by residential area and size of urban settlement in 2018. *Source* [54]

inhabitants. Such cities, regarded as medium-sized in line with the global standards, are in fact the biggest cities in 85 countries or regions. While a majority of capitals in the world are smaller, almost 40% of capitals are medium-sized cities [54].

Figure 9 presents the breakdown of global population in 2018 by the residential area (rural or urban) and city size.

Megacities, due to their size and concentration of business activity, are a huge challenge. In 1990, there were 10 cities with more than 10 million inhabitants. Currently, this number has grown threefold to 33, and the majority of megacities are located in Asia (Tokyo, Jakarta, Seoul, Delhi, Shanghai, Manila, Karachi, Mumbai, Beijing, Dhaka, Osaka, Kolkata, Tianjin, Shenzhen, Guangzhou, Bangkok, etc.). 13% of city inhabitants in the world presently live in megacities.

Figure 10 presents the population and number of cities in the world by city size in 1990, 2018 and 2030.

It is forecasted that the number of megacities in 2030 will have increased by another 10, from 33 to 43 megacities. The number of large cities with the population of 5–10 million is expected to increase from 48 to 66, the number of medium-sized cities with the population of 1–5 million is supposed to increase from 467 to 597, whereas the number of cities with the population of 500,000–1 million inhabitants should change from 598 to 710.

Figure 11 presents the percentage share of urban population in specific geographical areas in 2018. Overall, 48% of global population in 2018 lived in cities below 500,000 inhabitants. The largest share of population in such cities was in Europe (65%) and Africa (55%), whereas the smallest percentage was in North America (32%). Overall, 10% of global population lived in cities of 500,000–1 million inhabitants. There was more than 10% of inhabitants in such cities in North America (12%) and Europe (11%), whereas the smallest percentage was in Oceania (only 2%). On a

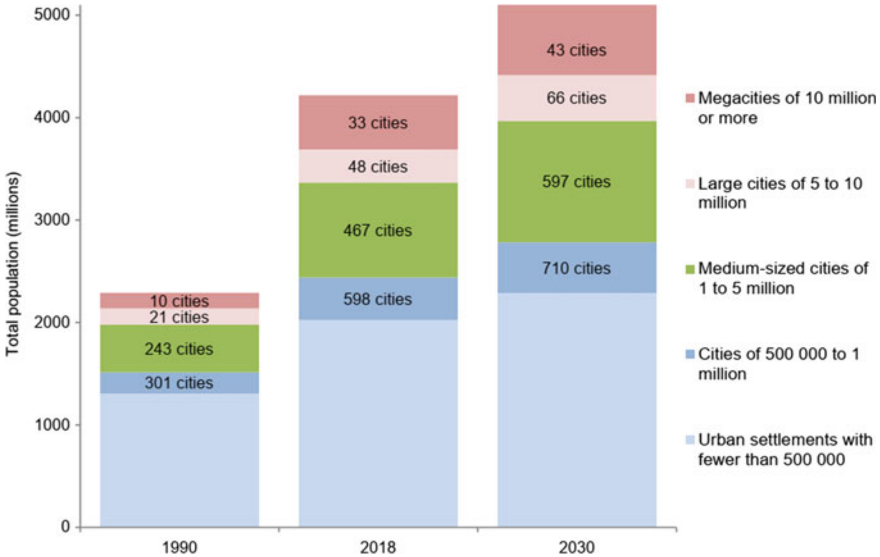

Fig. 10 Population and number of cities in the world by city size in 1990, 2018 and 2030. *Source* [54]

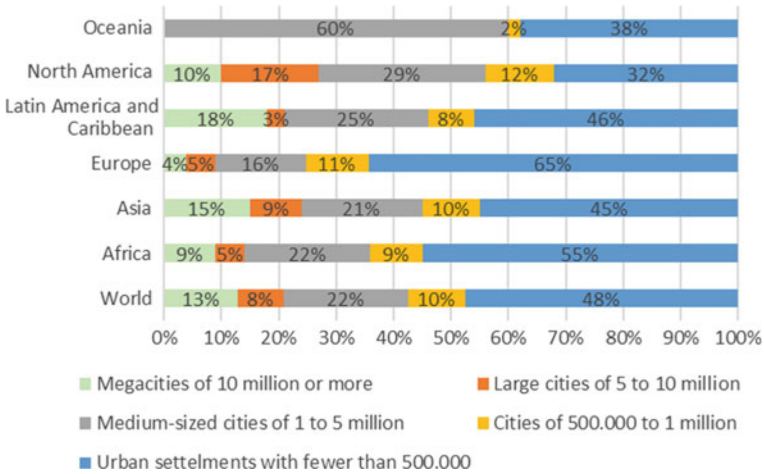

Fig. 11 Urban population in percent in specific geographical regions in 2018. *Source* [54]

global scale, 22% of population lived in medium-sized cities of 1–5 million inhabitants. The largest percentage share of population in cities of this size was in Oceania (60%) and North America (29%), whereas the smallest share was in Europe (16%). In large cities with the population of 5–10 million, the global percentage share of population amounted to 8%. The largest percentage share of population in such cities was in North America (17%) and Asia (9%), whereas the smallest share was in Latin America and the Carribeans (3%), as well as Europe and Africa (5% each). The total number of global population living in the megacities of 10 million or more inhabitants was 13%. The largest share of this population was in Latin America and the Carribeans (18%), followed by Asia (15%), whereas the smallest percentage share was in Europe (4%). There were no large cities or megacities in Oceania.

Overall, the largest percentage of population in large cities and megacities, i.e. cities with more than 5 million or more inhabitants, was in North America (27%), Asia (24%), as well as Latin America and the Carribeans (21%). They were followed by Africa (14%), while Europe had the smallest share (9%). The largest share of population in cities below 1 million was in Europe (76%) and Africa (64%), then Asia (55%), Latin America and the Carribeans (54%), North America (44%) and Oceania (40%).

The concentration of population and business activity in urbanised areas brings many benefits, but also negative effects. The positive aspects of city development include [55]:

- well-developed social and technical infrastructure (health service, educational, cultural, scientific, commercial and financial institutions),
- diverse labour market,
- enhanced work performance,
- formation of a large sales market,
- specialisation and diversity,
- bigger possibility to choose between different jobs,
- research and development, innovation,
- development of the creative class,
- easy communication and information flow, etc.

On the other hand, the negative effects include:

- excessive emission of dust, greenhouse gases, noise and waste,
- production of huge amounts of municipal and industrial waste, as well as problems with their storage,
- increased costs of public transport operation and residential housing,
- overloaded transport infrastructure and extended commuting time, traffic jams (congestion) on access roads, lack of parking spaces,
- water shortage,
- increase of crime rate and social pathologies,
- increase of aggression and social tensions, problems with immigrants,
- reduced sense of safety among inhabitants,
- increase of the number of homeless and unemployed, as well as the related expansion of poverty districts—social exclusion and poverty,
- social and economic inequalities,
- increased frequency of diseases caused by environmental factors (heart diseases, cancers and chronic diseases of the respiratory system), etc.

Understanding of the key urbanisation trends that may be revealed in the upcoming years is very important for the implementation of the 2030 Agenda for Sustainable Development [56], including the efforts for the preparation of a new development framework for urban areas. With the progressing global urbanisation, sustainable development is increasingly dependent on the effective management of city development, particularly in low- and medium-income countries, where the urbanisation rate is expected to be the fastest. Many countries will face challenges related to fulfilling the needs of the growing city population, including housing, transport, energy systems and other infrastructure, as well as employment and fundamental services, such as education and health care. There is a need for integrated policies, intended to improve the quality of life of city inhabitants based on the already existing economic, social and environmental links. In order to ensure that the benefits of urbanisation are fully shared and contribute to social inclusion, the management policies of city development must provide everyone with access to infrastructure and social services, focusing on the needs of city inhabitants that are particularly sensitive from the point of view of housing, education, health care, decent work and safe environment [57].

The 2030 Agenda for Sustainable Development sets out 17 sustainable development goals together with 169 related tasks. The following goals can be mentioned [56]:

- promotion of stable, sustainable and inclusive economic growth,
- development of stable infrastructure, promotion of sustainable industrialisation and support of innovation,
- making cities and human settlements safe, stable and sustainable places that promote social inclusion.

The following tasks were defined in connection with the specified goals [56]:

- reaching a higher level of economic performance through diversification, technological modernisation and innovations, as well as focusing on sectors with high added value and high work consumption ratio,
- promotion of development policy supporting production activity, entrepreneurship, creativity and innovations,
- building reliable, sustainable, durable and stable infrastructure of good quality, including regional and cross-border infrastructure, supporting the economic development and human well-being,
- until 2030—modernisation of infrastructure and industry to ensure its sustainable development, with the increased effectiveness of resource use and application of clean and environmentally-friendly production technologies and processes,
- until 2030—providing all people with access to safe, affordable, sustainable and easily accessible transport systems, increasing the safety level on roads, especially by public transport development, particularly focusing on the needs of vulnerable groups, i.e. women, children, as well as handicapped and elderly persons,
- until 2030—reduction in per capita ratio of adverse urban impact on the environment, particularly focusing on the air quality, as well as management of municipal waste and other types of waste,

- until 2030—ensuring easy and universal access to safe green areas encouraging social integration and safe public space,
- supporting economically, socially and environmentally beneficial connections between urban, suburban and rural areas by enhancing land use planning at the domestic and regional level.

The above-mentioned statements indicate how great importance is attached to stable, sustainable and inclusive development, supported by IT technologies, innovation and creativity, as well as to safe and available public transport. Apart from the demographic changes related to urbanisation processes, the process of society ageing is a significant trend, especially in the European countries.

The increased share of elderly persons in the population structure most frequently results from two factors: falling birth rate that leads to a decreased share of the youngest age groups and the rise of the average life expectancy due to the development of medicine and ongoing improvement of the living conditions. In the European Union (EU) countries where the urbanisation processes began the earliest, the population aged over 65 in 2006–2016 increased by 2.4% (from 16.8 to 19.2%). For the EU countries, a further increase of the number of elderly persons is forecasted until 2080. The forecast also distinguishes the age group over 80, in which the largest increase of people will take place (2016-5.4%, 2020-5.9%, 2030-7.2%, 2050-11.1% and 2080-12.7%). The percentage of people aged 65–79 will increase at a slower rate (2016-13.8%, 2020-14.5%, 2030-16.7%, 2050-17.4% and 2080-16.4%) [58]. The global percentage of people aged over 60 in 1950 was 8%, in 2010 it was 10%, whereas the forecast for 2050 is 21%.

These megatrends will set new challenges and expectations of the population in urbanised areas regarding the conditions and quality of life. An important aspect is the use of innovative technologies, especially with reference to urban transport system, in order to ensure sustainable urban mobility. In respect of mobility, this concerns activities in the field of: traffic management, car park management, collection of fees for transport and congestion, integrated mobility management, infrastructure for charging electric vehicles and payment solutions [59].

Sustainable mobility covers several aspects and components: sustainable and energy-saving public transport systems; friendly environment for other types of transport, such as cycling and walking; easy access to all districts, on foot, by bike or public transport; local transport networks which must be connected well with the regional networks.

Transport congestion is a very adverse phenomenon, because it directly impacts the urban environment, leading to low air quality, noise emission, high CO_2 level and problems with safety on the road, which is reflected in the assessment of the quality of life in cities.

As results from TomTom Traffic Index report [60], which describes the situation on roads in 403 cities from 56 countries around the world, the biggest congestion problem was in the largest cities in the world. In 2018, the most traffic jammed city was Mumbai (India), where the so-called traffic congestion index was 65%, which means that drivers from the most populous city in India spent 65% more time on the road in comparison with the average travel time without obstacles. The further positions in the ranking were taken by the capital of Colombia, Bogota (63%), Lima in Peru (58%), New Delhi in India (58%) and capital of Russia, Moscow (56%). The other cities in the global top ten were Istanbul (Turkey), Jakarta (Indonesia), Bangkok (Thailand), Mexico City (Mexico) and Recife (Brazil).

The following European cities had the biggest congestion problems in 2018: Moscow, Istanbul, Bucharest, Saint Petersburg, Kiev, Dublin, Łódź, Novosibirsk, Kraków and Edinburgh.

Among the Polish cities, Łódź reached the highest place in the global ranking, taking the 15th position in the world with the traffic congestion index amounting to 44%. Łódź was also ranked 8th among the European countries. The subsequent positions were taken by: Kraków—40%, Poznań and Warsaw—38%, Wrocław—35%, Bydgoszcz—32%, Gdańsk, Gdynia and Sopot—30%, Szczecin—27%, Lublin and Białystok—25%, Bielsko-Biała—20% and Katowice (agglomeration area)—16%.

Due to this, mobility in cities faces numerous challenges, the most important of which is road congestion and high dependence on cars, which has led to blockage of urban areas. The improvement of sustainable mobility in cities goes beyond the focus on the improvement of efficiency and effectiveness of transport systems, covering also in particular the demand-driven modes of transport, such as the promotion of walking, cycling and reduction of travel needs.

3.2 Mobility in the European Union Documents

The concept of sustainable mobility in cities is related to the goals concerning the improvement of both energy consumption and environmental indicators in cities. The European Commission indicates the need to undertake actions intended for better mobility planning, taking into account the principle of sustainable development [61].

The foundation for creating an integrated transport system in the countries forming the European Union is the common transport policy, the legal basis of which has already been included in the EEC Treaty of Rome [62]. The European Union countries strived to develop a common transport policy and form a coherent transport system, which was the basis for the efficient operation of the internal market. Along with the development of the European Union, further issues and areas covered by the common transport policy appeared, such as e.g.: effective development of transport system, taking into account the rules of market economy and fair competition, liberalisation of transport service market, creation of uniform transport and telecommunications infrastructure, design and development of new transport technologies [63], integration of public and individual transport, ensuring sustainable transport development.

Specific issues were the object of documents published by the European Commission, such as Green and White Books, as well as Communications.

Common transport policy is intended to increase mobility, remove the main barriers in key areas, as well as accelerate the economic growth and increase employment. An important goal is to reduce Europe's dependence on the import of oil and reduce carbon dioxide emission in the transport sector by 60% until 2050. The key goals for 2050 include:

- withdrawing conventionally-fuelled vehicles from use in cities,
- reaching the 40% level of using sustainable low-carbon fuels in aviation,
- reducing the emission level in the maritime transport sector at least by 40%,
- shifting 50% of intercity passenger traffic to medium distance and transport of goods from road to railway and sea.

All these changes are supposed to contribute to reducing total transport emissions in the first half of this century by 60%. Other issues included in the EU transport policy concern infrastructure planning, application of IT technology, safety, passenger rights and international cooperation [64].

Many European cities face difficulties connected with transport and traffic, or the related problems (congestion, air pollution and noise, safety on the road). Taking into account the growing population inhabiting urbanised areas and current problems resulting from the inefficiency of urban transport system, it is necessary to pay more attention to the solutions promoting sustainable urban mobility. Economic and social transformation rapidly increased the mobility level. The growing use of private cars was accompanied by the spatial growth of cities and increase of commuting to work, whereas in many cases the public transport network did not develop at the same rate [65]. The development of current EU urban transport policy has a long history.

In 1992, the European Commission presented the Green Paper on the Impact of Transport on the Environment: A Community Strategy for Sustainable Mobility [66]. The Green Paper contained the assessment of the general impact of transport on the environment and outlined the common strategy for sustainable mobility which should enable transport to perform economic and social functions, while at the same time reducing harmful environmental effects. Special attention was paid to air pollution, noise and congestion problem, which was defined as a recurrent temporary phenomenon of variable duration, resulting from the lack of balance between the demand and supply of transport infrastructure capacity. The effect of this lack of balance is the overloading of transport infrastructure and congestion. It has been noticed that congestion, which is characteristic for urban traffic, also begins to be a problem in air transport. The basic consequences of the congestion phenomenon in cities include the possible reduction of mobility, increase of pollution and energy consumption, as well as ineffective use of time. Moreover, other identified possible effects of congestion include the loss of comfort and well-being, decrease of income and production, as well as reduced rest time. The following instruments that can be used for reducing congestion were indicated: proper public transport systems with a high utilisation rate, traffic management systems, road tolls and restricted availability of crowded areas for passenger cars. The purpose of this document was to initiate a public debate on how to reach the goals of the presented strategy for sustainable mobility.

The Green Paper was also connected with the European Commission's statement of 1998 entitled Common Transport Policy—Sustainable Mobility: Perspectives for the Future [67]. This document emphasized the significance of integrated transport systems, easily available and safe transport services, including in peripheral and less developed regions, in order to increase the competitiveness of Europe, economic growth and employment. High importance was attached to technical progress and telematics in effective and sustainable development of integrated transport systems as one of the key priorities for the Commission. The improvement of the quality of local public transport, which is the only form of transport available to all citizens (especially in large cities), was indicated as a great challenge. The document also highlighted the negative transport impact on the natural environment, because the development of transport systems cannot take place at the expense of the quality of life of citizens, or cause environmental degradation. Therefore, environmental protection was considered to be an integral part of the transport policy and the need was identified to enhance the environmental assessment by political initiatives that have significant impact on the environment [68]. It was emphasized that common transport policy is a developing, dynamic instrument designed in order to provide an integrated European transport system.

On 12 September 2001, the Commission of the European Communities presented the White Paper "European Transport Policy 2010: Time to Decide" [69]. It outlined the directions of transport policy of the European Union until 2010, emphasizing the importance and validity of the previous goal of the EU transport policy, i.e. sustainable development, indicating the need to manage the development of transport system in a more sustainable way. The document highlighted the disparities in the development of specific modes of transport and domination of road transport. Congestion, whose external costs (only in road transport) were estimated at approximately 0.5% of the Gross Domestic Product of the European Community, was named as a serious risk of losing competitiveness by the European economy. It was also assessed that if no actions are taken in this respect, the expected traffic growth by 2010 will also cause an increase of congestion costs even by 142%, thus reaching the total annual amount of EUR 80 billion, which is 1% of GDP of EC. The problem of congestion was partly explained by the fact that transport users do not always pay the costs that they generate. As a result, the price structure does not generally reflect the entire costs of infrastructure, congestion, environmental impact and accidents. The White Paper included sixteen specific proposals to be undertaken at the community level as part of the transport policy. The development of high quality urban transport was indicated among the detailed proposals. The Community suggested giving priority to better use of public transport and existing infrastructure in the light of the general degradation of the quality of life of European citizens.

The following stage of EU transport policy consisted in adopting the "Green Paper—Towards a New Culture for Urban Mobility" on 25 August 2007 [70]. Urban mobility was recognised there as an important factor contributing to economic growth and employment, having a great impact on sustainable development in EU. The document presented a new approach to urban mobility, consisting in the optimised use of different modes of public and individual transport, as well as creating good conditions for the execution of intermodal journeys by means of various public transport systems (railway, metro, bus, taxi) and individual transport (car, motorbike, bike, walking). The following five main challenges concerning transport in cities that require an integrated approach were specified:

- increase of traffic fluidity in the cities,
- problems related to excessive use of passenger cars and road transport,
- implementation of smart transport systems,
- improvement of the availability of public transport,
- increase of the reliability and security of public transport.

Certain possible activities were indicated in order to face these challenges. In order to increase the traffic fluidity in cities, efforts should be made to raise the attractiveness of alternative forms of movement, in particular public transport, bike transport and pedestrian movements. This also includes promotion of new solutions, such as the joint use of one car for commuting to work and school, integration of public and individual transport thanks to the creation of Park&Ride transport nodes, proper infrastructure management, popularisation of ecological and energy-saving vehicles, smart traffic management systems, toll collection, etc. Particular attention was paid to the development of new urban mobility culture through education, trainings and raising awareness of the importance of sustainable mobility. The problem of mobility is complex and covers several interrelated aspects (environmental, economic and social). The examples of actions named included encouraging eco-driving (in driving schools and courses for professional drivers), thanks to which the energy consumption is reduced. Another specified item was the significance of user-friendly, proper and interoperable multimodal travel information when planning journeys, to provide travellers with the possibility of conscious choice of modes of transport and travel time. Attention was also paid to the need to develop uniform rules on green zones in cities (pedestrian only zones, restricted access zones, speed limits, urban tolls, etc.) at the EU level in order to enable application of similar solutions to a wider extent, without creating disproportionate obstacles for the mobility of people and goods at the same time.

As specified in the Green Paper of 2007 “Towards a New Culture for Urban Mobility”, there is no single solution for reducing congestion in cities. The problems of urban mobility are strictly related to the main features of modern economy and society (hypermobility of people, goods and information) and have a big impact on the structure and organisation of a majority of global metropolitan areas [71]. Therefore, ecological solutions should be developed and promoted in order to reduce the negative impact of transport on the urban area environment, i.e. harmful emission, noise, etc. [72].

Another document concerning urban mobility is the Communication from the European Commission—“Action Plan on Urban Mobility” [73] of 2009, indicating practical actions to address the problems of sustaining mobility in cities in an integrated manner. The proposed actions cover six basic areas:

- promoting integrated policies (accelerating the take-up of sustainable urban mobility plans, sustainable urban mobility and regional policy, transport for healthy urban environments),
- focusing on citizens (platform on passenger rights in urban public transport, improving accessibility for persons with reduced mobility, improving travel information, access to green zones, campaigns on sustainable mobility behaviour, energy-efficient driving as part of driving education),
- greening urban transport (research and demonstration projects for lower and zero emission vehicles, Internet guide on clean and energy-efficient vehicles, study on urban aspects of the internalisation of external costs, information exchange on urban pricing schemes),
- strengthening funding (optimising existing funding sources, analysing the needs for future funding),
- sharing experience and knowledge (upgrading data and statistics, setting up an urban mobility observatory, contributing to international dialogue and information exchange),
- optimising urban mobility (urban freight transport, intelligent transport systems (ITS) for urban mobility).

The document outlines that urban mobility consistent with the rules of sustainable mobility has a growing importance in relations with neighbours and global society, which is increasingly concentrated in urban agglomerations.

2010 marked the creation of the Community development strategy, which also raises the issues of sustainable mobility. Europe 2020—A strategy for smart, sustainable and inclusive growth [74] is a document outlining the long-term vision of the development of the European Union until 2020. Europe 2020 puts forward three mutually reinforcing priorities:

- smart growth: developing an economy based on knowledge and innovation;
- sustainable development: promoting a more resource efficient, greener and more competitive economy;
- inclusive growth: fostering a high-employment economy delivering social and territorial cohesion.

The problems of urban transport and mobility were included as part of actions towards smart and sustainable development.

In the White Paper "Roadmap to a Single European Transport Area—Towards a competitive and resource efficient transport system" of 2011, ten goals were set for a competitive and resource efficient transport system. The document outlined that further development of the transport sector should be based on several assumptions, including e.g.: improving the energy efficiency performance of vehicles across all modes (developing and deploying sustainable fuels and propulsion systems), optimising the performance of multimodal logistic chains, as well as using transport and infrastructure more efficiently thanks to application of improved traffic management and information systems. For urban areas, development of strategies involving e.g.

land-use planning, pricing schemes, introduction of intelligent intermodal ticket system, efficient public transport services, infrastructure for non-motorised modes and charging/refuelling of clean vehicles were indicated as necessary. Creation of better conditions for walking and cycling should also become an integral part of urban mobility and infrastructure design.

In Annex I to the White Paper "List of Initiatives", the analysis of the possibility to introduce mobility plans as the obligatory solution for cities of specific size was specified as one of the actions to be taken [75]. The recommendations included in the document whose time horizon reaches 2050 concern the following areas:

- growing transport sector and supporting mobility while reaching the 60% greenhouse gas emission reduction target,
- development of an efficient core network for multimodal intercity travel and transport,
- global level-playing field for long-distance travel and intercontinental freight,
- clean urban transport and commuting,
- specifying goals for a competitive and resource efficient transport system.

The document identified the need to provide systemic support for the development and implementation of mobility plans, as well as to include such plans in the context of distribution of EU funds. Cities above a certain size should be encouraged to develop urban mobility plans, fully aligned with integrated urban development plans. In the urban context, it is necessary to reduce congestion, noise and emission of harmful substances, because these are the biggest problems in cities. Switching to cleaner transport in cities is facilitated by lower requirements for vehicle range and higher population density, which will contribute to gradual elimination of conventionally-fuelled vehicles from cities. New technologies for vehicles and traffic management will also have an impact on reducing transport emissions. Moreover, it has been found that information and communication technologies have the potential to satisfy certain accessibility needs without additional mobility.

In December 2013, the European Commission adopted the Urban Mobility Package, reinforcing its supporting measures in the area of urban transport by:

- sharing experiences, show-casing best practices and fostering cooperation,
- providing targeted financial support,
- focusing research and innovation on delivering solutions for urban mobility challenges.

The central element of the Urban Mobility Package is the Communication "Together towards competitive and resource efficient urban mobility" [76]. According to the European Commission, a step-change in the approach to urban mobility is required to ensure that European urban areas develop along a more sustainable path and that EU goals for a competitive and resource-efficient European transport system are met. It is also crucial to overcome fragmented approaches and develop the single market for innovative urban mobility solutions by addressing the issues such as common standards and specifications or joint procurement. The implementation of systemic actions towards sustainable mobility requires cooperation between public entities at all levels of government and involvement of the private sector. It is supplemented by an annex that presents the concept of Sustainable Urban Mobility Plan, as well as four working documents on urban logistics, regulations concerning access to cities, implementation of intelligent transport system solutions in cities, as well as areas and safety of urban road traffic. The Commission decided that urban mobility is primarily a duty of relevant units at the local level and focused on developing new integrated strategies for sustainable urban mobility, as well as transport plans that may constitute the basis for their successful implementation. In this context, the Commission presented the concept of Sustainable Urban Mobility Plans (SUMP) and also focused on the following areas: urban logistics, urban access regulation, deployment of ITS solutions in urban areas and urban road safety [77]. In particular, the high potential of ITS for optimisation of urban mobility and achievement of policy goals, such as e.g. increasing safety and reducing congestion, was highlighted. With reference to urban logistics, it is possible to contribute to reducing noise and congestion, as well as to improving travel effectiveness thanks to better management. On the other hand, the regulations concerning vehicle access to urban traffic may restrict the use of highly polluting vehicles, as well as encourage the use of quieter, low-carbon vehicles. Thanks to the road traffic safety measures, it is possible to encourage better vehicle handling, which should contribute to reducing the general level of emission, while at the same time reducing the number of accidents in transport network and the related congestion. The importance of information technologies in supporting new mobility patterns was emphasized, based on the interconnected use of all modes of transport (e.g. multimodal journeys), information about road traffic in the real time, integrated multimodal electronic toll systems, as well as the programmes for joint use of cars and bikes.

SUMP is a strategic plan created in order to fulfil mobility needs of people and economy in cities and their surroundings to achieve a better quality of life. It is based on the existing planning practices and takes into account the principles of integration, social participation and process evaluation. The goal of SUMP is to present targeted integrated actions, clearly leading to a growth of sustainable transport and increase of society mobility in the area covered by planning [78]. For the purpose of effective implementation of SUMP, it is necessary to use a number of instruments, measures, tools and strategies that will consequently enable sustainable urban mobility. The basic instruments include legal, planning, investment, financial instruments, as well as instruments related to the creation, sale and reservation of mobility products, coordination and organisation of transport solutions and services, educational, informational and promotional activities that may influence a change in the transport behaviours of urban population [79–81]. A significant role in these solutions is attributed to public urban transport, which may become a more attractive form of movement than personal car thanks to certain technical, economic and organisational solutions. Moreover, attention was paid to the fact that instruments that are part of sustainable urban mobility should increase the number of people walking, cycling and using public transport, thus not only contributing to reduction of emission and noise generated by road traffic, but also leading to higher availability for everyone and bigger equality in transport system, increase of physical activity and improvement of public health.

The document of the European Commission—Communication from the European Commission to the European Parliament, the Council, the European Economic and Social Committee, as well as the Committee of the Regions—European Strategy for Low-Carbon Economy was announced in 2016 [82]. The Communication stated low-carbon mobility as the necessary element for increasing transition to closed-loop low-carbon economy, which is required for Europe in order to maintain its competitiveness and be able to adjust to the needs in respect of the mobility of individuals and the movement of goods. It was also emphasized that digital technologies could make transport safer, more effective and inclusive. For the best use of their potential, these technologies must be well integrated with the mobility concepts that are consistent with the principles of sustainable development. Due to this, the implementation of intelligent transport systems in all types of transport becomes an integral part of the development of multimodal trans-European transport network. Digital technologies have a strong potential for optimisation of the transport system and create many options for the production sectors. These technologies also support transport integration with other systems, such as the energy system, and increase the effectiveness of operations in the mobility sector. The perspectives for development of low-carbon alternative energy sources in specific types of transport are different. The widest range of options currently exists with reference to passenger cars and buses. The goal of activities for low-carbon mobility is to increase the effectiveness of transport system, as well as alternative low-carbon energy sources for the purpose of transport and development of low-carbon and zero emission vehicle market.

The application of digital solutions in transport is consistent with the Directive of the European Parliament and of the Council of 7 July 2010 on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport [83]. Intelligent Transport Systems (ITS) are information and transport systems intended to provide services related to various modes of transport and traffic management, delivering better information to different users, as well as ensuring a more secure, coordinated and 'intelligent' use of transport networks. They are intended for traffic management, mobility management and may cooperate with similar systems applied in other types of transport. Intelligent Transport Systems (ITS) constitute a set of tools based on IT and telecommunications technologies, as well as telematics solutions applied in order to increase the effectiveness and integration of the entire transport system in a city according to the rules of sustainable development [84].

In May 2016, twenty-eight ministers with representatives of other EU institutions and representatives of European cities signed the Pact of Amsterdam concerning the so-called Urban Agenda for the EU, a document laying down the rules for implementation of the urban agenda [85]. Urban Agenda for the EU is a forum [86] attended by the Commission, national ministries, municipal authorities and other stakeholders. The goal is to develop better regulations, facilitate access to financing and exchange knowledge of important subjects from the perspective of cities [85].

It established cooperation between various authority levels in EU, as well as business and social partners within the framework of partnerships in 12 priority areas. Thanks to the establishment of partnerships with the participation of municipal authorities, Member States, EU institutions and other stakeholders, including non-governmental organizations and enterprises, Urban Agenda will contribute to supporting the economic and social development of Europe. Its goal is to provide citizens with new opportunities, improve their quality of life and meet the key challenges faced by cities—starting from the problems of employment and social inclusion, ending with mobility, environment and climate changes, because successful development of cities has a big impact on the economic, social and environmental growth across Europe, and therefore, it is the key element of implementation of goals for intelligent and durable economic growth that supports social inclusion. The priority areas of the Urban Agenda include [87]:

- air quality,
- closed-loop economy,
- adjustment to climate change,
- digital transition,
- energy transition,
- housing,
- social inclusion of migrants and refugees,
- innovative and responsible public procurement,
- jobs and skills in the local economy,
- sustainable land use and solutions based on natural resources,
- urban mobility,
- urban poverty.

Priorities in the social and economic aspect include creation of new jobs and development of education as part of local economy, fight against poverty, solving problems related to housing and mobility, as well as initiatives supporting the integration of foreigners and refugees. Much attention was also paid to environmental challenges, including sustainable land-use planning, building circular economy, adjustment to climate changes, energy consumption and air quality. The key rules of Urban Agenda include [88]:

- working method based on partnership,
- mechanism of cooperation on many levels,
- focus on integrated approach,
- sustainable development strategy,
- fulfilment of UN Sustainable Development Goals,
- building functional urban areas,
- building connections between urban and rural areas,
- adjustment to the needs of cities of all sizes.

The goal of Partnership for Urban Mobility (PUM) was to offer solutions to improve the framework conditions of urban mobility in cities across EU. The solutions were related to problems important for technological progress, encouraging the use of active modes of transport, improving public transport and promoting multi-level management measures. Initially, PUM put an emphasis on the following four subjects: active modes of transport and use of public space, innovative solutions and smart mobility, public transport for the city/region, as well as multimodality and management. Having identified the challenges, bottlenecks and potentials, specific working groups were defined in order to develop the action plan intended to improve: (a) EU regulations concerning urban mobility, (b) use and allocation of EU funds, as well as (c) platforms for exchange of knowledge and their use [89].

In 2017, the European Commission announced the White Paper on the future of Europe. Reflections and scenarios for the EU27 by 2025 [90]. This document presented five potential scenarios intended to support the debate about the future of Europe, each of them based on the assumption that the European Union will still consist of 27 Member States. The scenarios are as follows:

- Scenario 1: Carrying on—the European Union focuses on delivering its positive reform agenda.
- Scenario 2: Nothing but the single market—the European Union is gradually re-centred on the single market.
- Scenario 3: Those who want more do more—the European Union allows willing Member States to do more together in specific areas.
- Scenario 4: Doing less more efficiently—the European Union focuses on delivering more and faster in selected policy areas, while doing less elsewhere.
- Scenario 5: Doing much more together—the European Union decides to do much more together across all policy areas.

There were advantages and disadvantages specified for each scenario. Each scenario also determined the impact of actions on uniform market and trade, economic and monetary union, Schengen Area—migration and safety, foreign policy and defence, as well as ability to act.

During the unofficial meeting of EU Ministers Responsible for Urban Matters in Bucharest on 14 June 2019, the Declaration of Ministers "Towards a common framework for urban development in the European Union" was adopted [91]. The Declaration emphasized that cities and urban areas play an important role in delivering EU priorities. The development of urban areas has a large potential to contribute to territorial cohesion of the EU by creating positive externalities beyond urban areas. It is crucial to pursue the added-value of the integrated territorial development and 'urban ownership' as promoted by the Cohesion Policy. Finally, it is necessary to continue the efforts towards the Urban Agenda for the EU process and to actively support the development and the implementation of actions under the Urban Agenda for the EU.

Further documents were issued in January 2019: Document opening the Reflection Paper "Towards a Sustainable Europe by 2030" [92] including three annexes. Annex I: The Juncker's Commission's contribution to the Sustainable Development Goals [93], Annex II: The EU's performance on the Sustainable Development Goals [94] and Annex III: Summary of the contribution of the SDG Multi-Stakeholder Platform to the Reflection Paper "Towards a Sustainable Europe by 2030" [95]. The Reflection

Paper “Towards a Sustainable Europe by 2030” outlined the key factors enabling changes towards a sustainable Europe by 2030:

- education, science, technology, research, innovation and digitisation,
- finance, pricing, taxation and competition,
- corporate social responsibility,
- open and rules-based trade,
- governance and policy coherence,
- EU as a global trail blazer.

The document outlines three scenarios of effective actions towards the implementation of SDGs [96]:

- Scenario 1: An overarching EU SDGs strategy to guide all actions by the EU and Member States
- Scenario 2: Continued mainstreaming of the SDGs in all relevant EU policies by the Commission, but not enforcing Member States’ action
- Scenario 3: Putting enhanced focus on external action while consolidating current sustainability ambition at the EU level.

In this way, the Commission began discussion on sustainable development in the future as part of a broader debate initiated in March 2017 by the White Paper for the future of Europe [90].

Annex I: The Juncker’s Commission’s contribution to the Sustainable Development Goals [93], with regard to urban mobility specified that in consequence of the strategy towards low-carbon mobility, the Commission adopted three packages supporting “Europe on the Move” mobility, in 2017 and 2018 respectively. “Europe on the Move” is a broadly designed set of initiatives that will increase the traffic safety, encourage to implement intelligent road toll collection systems, as well as reduce carbon dioxide emission, air pollution and traffic congestion. For this purpose, the initiatives have adopted an integrated policy for the future of road traffic safety, providing measures for the security of vehicles and infrastructure; the first ever CO_2 standards for heavy-duty vehicles; a strategic action plan for the development and manufacturing of batteries in Europe and a forward-looking strategy on connected and automated mobility.

Joint Research Centre (JRC) of the European Commission published in 2019 a report on “The Future of Cities—opportunities, challenges and the way forward”. The report is a part of “Facts4EUFuture”, a series of reports on the future of Europe. “The Future of the Cities” report was presented during the European Week of Regions and Cities on 11 October 2019, identifying trends, asking questions and provoking discussions on what the future of cities may and should be [97]. According to the report, some cities in Europe will grow, while others will decrease, whereas it is expected that urban population will continue to grow in a majority of Earth. Brussels, Luxembourg and Stockholm may grow by over 50% by 2050. 25–50% increase by 2050 is expected mainly in medium-sized capital cities, such as Vienna, Budapest, Prague, and big regional cities in France, as well as Munich and Bologna. The population decrease exceeding 25% will mainly take place in small and less populated cities in eastern Germany, Spain, Latvia, Lithuania and Bulgaria. Europe will have to face challenges related to the decrease and ageing of population in many cities. The report also indicated other trends:

- It is expected that a majority of European cities will increase geographically, and cities will have to recognise better the importance of optimising the way that their public space is designed and used.
- The ageing EU population will require further adjustment of infrastructure and services.
- Cities will increasingly use new technologies and innovations in transport and mobility. These technologies will have to integrate seamlessly with one another and bring benefits to all citizens.
- The car dominance could be drastically reduced in favour of more efficient public transport, as well as shared and active mobility. Transport demand can also be reduced by means of new working patterns.

Shaping urban mobility requires coordinated actions on the part of decision-makers and relevant authorities at all administration levels. The European Commission has been actively supporting and initiating cooperation projects related to sustainable urban mobility for decades, beginning with research, development of tools, presentations, trainings, popularisation and other measures for exchange of knowledge.

Generally speaking, the improvement of urban mobility consists in changing the mobility culture of planners, decision makers and users. Since private cars better satisfy the user requirements concerning the safety, reliability and availability of mobility needs, the planners and decision makers mainly face the challenge of providing effective alternatives to car. This also concerns research and innovation, as well as development of smart and innovative solutions for public transport systems. The problem of urban mobility is a priority for the EU, but it also becomes increasingly important in other regions of the world, taking into account the trends in urbanisation, car ownership and public transport. In the future, the urbanisation rate will mainly concern the developing countries. The forecasts regarding global vehicle fleet also show that it is supposed to grow from 800 million to 2–3 billion, because middle class in the developing countries is becoming richer and more dependent on private cars. Regardless of the concerns related to energy supplies, climate changes or congestion costs, it is expected that the share of public transport in modal transport during the upcoming decade will decrease in all parts of the world [98].

Eltis—The Urban Mobility Observatory is a platform that plays an important role in supporting activities in the field of planning sustainable urban mobility. The urban mobility website Eltis was launched in 2000. It has become the central website for all problems related to urban mobility. Eltis facilitates an exchange of information, knowledge and experiences in the area of sustainable urban mobility in Europe [99].

4 Transport Behaviours of the Polish Creative Class

4.1 Characteristics of the Study Group

The term "creative class" was proposed by R. Florida in his paper from 2002 entitled "The Rise of the Creative Class" [100]. The basis for identification of this social group is performance of work that consists in creating new and significant forms. This division is strongly connected with the direction of professional activity of its representatives. R. Florida distinguished two subgroups of the creative class:

- super-creative core formed by scientists, engineers, artists, designers and architects, programmers, representatives of opinion leaders (e.g. non-fiction authors, publishers, analysts),
- creative professionals working in the fields that require advanced knowledge and skills, e.g. individuals employed in legal professions, hi-tech sector, financial services industry, health protection and management specialists.

The cross section of creative class is very broad from the perspective of professional activity, and the common factor is the lack of repeatability of work performance. According to R. Florida, the core of the creative class is focused not only on solving problems, but also, or perhaps mainly, on looking for such problems. The creative class is supplemented by representatives of the group of creative professionals whose actions are repetitive, but require professional knowledge and independent thinking. R. Florida has concluded that growth of the creative class is a characteristic distinctive mark of postindustrial societies. The hypotheses proposed by R. Florida quickly became a subject of further research, which has focused on three main areas: precise delimitation of the creative class, impact of the creative class on economy and mobility of this social group with regard to selection of the workplace and residence. The existing results of research on the creative class have been presented synthetically in Table 4.

Based on the presented research results, it may be concluded that the creative class is a driving factor for local and regional development. Its representatives are usually well-educated, implement non-standard projects, living in an open and tolerant environment. R. Florida described the development model related to the existence of the creative class using 3T: technology, talent, tolerance. Due to its social status, the creative class is opinion-forming, whereas its representatives are development leaders in their own local communities. Due to the presented characteristics, in the opinion of the authors, the creative class will be more willing to implement sustainable urban mobility, because:

1. The group members have a stable economic situation, so they will have a less negative attitude to restrictive activities, e.g. limitation of traffic for older vehicles (or diesel-engine vehicles) in the city centre.
2. Due to international contacts (e.g. work in a global company) and higher tendency for travel, they are willing to refer to foreign models in the context of solving local transport problems—e.g. road congestion, etc.

3. Representatives of the creative class are aware of the problem of transport impact on the environment (including natural environment) and are capable of changing their own transport habits with a view to improving the natural environment.
4. They are not concerned about the contact with modern technology and adapt to new solutions faster than the rest of the society.
5. A characteristic feature of the creative class is their openness and tolerance, which is also manifested by the acceptance for transport behaviours of other people who e.g. use the bike in commuting to work, etc.

For the above reasons, it was concluded that representatives of the creative class may be the foundation for implementing the instruments of sustainable urban

Table 4 Review of research on the role of the creative class in society and economy

Research authors	Method and scope	Main results
Boschma and Fritsch [101]	Analysis covering over 450 regions from 8 European countries	• Geographical distribution of the creative class is very uneven • Urban centres as such do not attract representatives of the creative class; it should be noted that the regional atmosphere of openness and tolerance has a significant and positive impact on the increase of the percentage of the creative class • The creative class has a positive and significant impact on the growth of employment and establishment of new companies at the regional level • Human capital measured by creative professions exceeds indicators based on formal education in terms of reliability
Mellander et al. [102]	Analysis of data from over 60 countries in terms of correlations between: happiness/creative class and income/economic level,	• There is a positive correlation between happiness (living satisfaction) and tolerance and social openness • GDP per capita and the percentage of the creative class have a significant impact on the perception of general happiness and living satisfaction • In the countries with relatively low income, GDP value has a higher impact on citizen satisfaction, whereas in the countries with relatively high income, it was demonstrated that the share of the creative class has a bigger impact on the level of satisfaction than economic indicators

(continued)

Table 4 (continued)

Research authors	Method and scope	Main results
Florida et al. [103]	Mathematical model of relations between the human capital and regional development of Canada, based on structural equations	• Tolerance and openness contribute to the development of the creative class • Tolerance plays a very important role in the regional development • The creative class is a better indicator describing the level of human capital than the average level of education or number of people with higher education
Florida et al. [104]	Mathematical model of relations between the human capital and regional development, based on structural equations, for the data from 331 metropolitan areas in the USA	• Creative sectors such as engineering, IT, management, business and financial services have a very significant impact on the regional development • The artistic circles are not only responsible for the consumption of regional resources, but also contribute to economic growth • Tolerance plays a significant role in attracting the creative class
Clifton [105]	Analysis of correlations and regressions between statistical data from the Great Britain	• The representatives of the creative class constitute approximately 37% of the inhabitants of England and Wales • The geographical distribution of the creative class is uneven—metropolises are the main attractive force • There is a high concentration of the creative class in the places that are tolerant, diversified and provide the possibility of participating in culture
Mellander and Florida [106]	Mathematical model of relations between the human capital and regional development of Sweden, based on structural equations	• The functioning of the creative class and industries better explains the income distribution than the traditional measures related to the education level • Representatives of artistic professions play an important role in the regional development process • The factors attracting representatives of the creative class include: openness, tolerance, technology

(continued)

Table 4 (continued)

Research authors	Method and scope	Main results
Lorenzen et al. [107]	Analysis of distribution of the creative class in Europe based on data from 445 cities	• Generally speaking, the creative class is characterised by a serial distribution of volumes; positive correlation between the city size and concentration of the creative class was demonstrated • The distribution has three stages, depending on the city size • In the case of small cities, i.e. below 70,000 inhabitants, the tendency for proportional growth of the European creative class is 1.52 times more negative, whereas in the case of cities above 1.2 million inhabitants, it is 1.13 times more positive
Stryjkiewicz and Męczyński [108]	Questionnaire survey conducted among representatives of the creative class from 13 European countries (including Poland)—ACRE project	• Mobility (understood as a change of residence) of the European creative class is significantly lower than in the case of American models • Average 48% of respondents worked in their place of birth, whereas there were significant discrepancies between specific countries • The following personal circumstances played the most important role in the choice of residence and job: place of birth and proximity of the family • Another element having an impact on the nature of the creative class mobility where was so-called hard factors, such as: structure of labour market, level of remuneration and obtained education • In terms of significance, the lowest classified factor was the soft conditions connected with the quality of life and working environment

mobility. Such people should be role models, especially in breaking the transport stereotypes that still exist in Poland (e.g. perception of car as a symbol of social status).

The goal of this chapter is to present the results of research on transport behaviours and postulates made by representatives of the creative class in Poland. The research was conducted on a target group, in three Polish metropolitan centres: Warsaw, Tricity and Silesia Metropolis (GZM).

Warsaw is the capital city, located in the central part of Poland, in Mazovia Province. It is characterised by the largest surface and highest number of population among Polish cities. Due to its nature, Warsaw is the centre of government and regional administration. Seats of many global companies are also located here. Warsaw has the leading position among Polish cities in providing services for business [109] and in the number of *start-up* projects located in the city [110]. Warsaw is an example of monocentric agglomeration, composed of one dominating main centre (core) with satellite towns and urbanised rural areas. The other centres covered by the research are polycentric, i.e. they consist of several main centres having a similar potential. Tricity, located in the Pomerania Province, includes three major cities: Gdańsk, Gdynia and Sopot, as well as a number of smaller towns. Similarly, as in the case of Warsaw, Tricity also plays an important role in terms of business, trade (especially related to sea traffic operation) and development. The study of behaviours of the creative class also covered people working in Silesia Metropolis (GZM). This area is a conurbation, and its core consists of thirteen neighbouring cities with district rights. Silesia Metropolis is located in the central part of Silesia Province, in southern Poland. A characteristic feature of this area is the existence of many practically equal urban centres where industry, modern technologies and well-developed academic network are concentrated. The basic parameters for the analysed areas were presented in Table 5.

In each of the above-named centres, 150 PAPI interviews were carried out. As a result, 450 fully completed questionnaire surveys were obtained for the entire study. The research was conducted from 15 July to 15 September 2019. The sample selection was targeted, whereas the study was carried out by the Research and Knowledge Transfer Centre of the University of Economics in Katowice. Due to the specific nature of the group, the research was conducted in selected enterprises that met the following two criteria: they were based in the above-named metropolises and classified in the creative industry group.

The professional structure of the research participants was as follows:

Table 5 Characteristics of the areas covered in the research on the creative class

Data range	Number of inhabitants (people)	Surface (km^2)	Number of passenger cars (vehicles)	Population density (people/km^2)	Motorization index (vehicles/1000 people)
Warsaw[1]	1,777,972	517	1,332,923	3439	750
Tricity[2]	748,986	414	463,543	1809	619
Silesian metropolis[3]	1,758,096	1065	938,049	1651	534

[1]Data for the city of Warsaw
[2]Aggregate data for: Gdańsk, Gdynia, Sopot
[3]Aggregate data for: Bytom, Chorzów, Dąbrowa Górnicza, Gliwice, Katowice, Mysłowice, Piekary Śląskie, Ruda Śląska, Siemianowice Śląskie, Sosnowiec, Świętochłowice, Tychy, Zabrze
Own study based on [111]

- artistic activity: 57.56%,
- research and development: 36.44%,
- advertising industry: 6.00%.

The general gender structure of the respondents involved in the study was: 61% women and 39% men. The results in particular metropolises do not show any significant differences. Only in Tricity, the percentage of women fell to 53%. For comparison, the population structure according to gender for the entire Poland in 2018 amounted to: 52% women, 48% men.

In the course of the conducted survey, a group of respondents coherent in terms of "metrics" (representatives of the creative class) was identified. A statistical member of this group is characterised by the following parameters:

- average age approximately 40–41,
- good assessment of the subjective economic situation,
- higher education.

When conducting the research using the survey questionnaire, the nature and location of work performance were applied. The respondents were not asked about the residence, because it is not important from the point of view of identification of the creative class. Narrowing down the number of locations to three metropolises is not accidental. In this way, responses were obtained from representatives of the southern, central and northern part of Poland. The metropolitan areas included in the study are also characteristic in terms of their transport conditions.

4.2 Survey Results

The representatives of the creative class consider car to be an important element of their journeys. The average number of passenger cars in households was 1.17 (with the median value equal to 1). The detailed data for particular metropolises are as follows:

- Warsaw: 1.18,
- Tricity: 0.99,
- Silesia Metropolis: 1.35.

Table 6 presents the structure of households in terms of the number of cars owned. The presented data indicate high attachment to car. The growing motorization index in Poland is a real phenomenon and shows a strong growing trend (Fig. 12). In the group of the respondents, only 14.2% households do not have a passenger car on the average, whereas 59.1% households have one passenger car and 22.9% households have two vehicles. These results are significantly different in the case of Silesia Metropolis, with a clear tendency of the inventory to increase. In this case, as much as 32% of households have two vehicles, 6% of households have three cars, and 2% of

Table 6 Number of cars in the households of respondents

Data range	No car (%)	1 car (%)	2 cars (%)	3 cars and more (%)
Overall	14.2	59.1	22.9	3.8
Warsaw	8.1	67.1	22.8	2.0
Tricity	18.0	66.7	14.0	1.3
Silesia metropolis	16.0	44.0	32.0	8.0

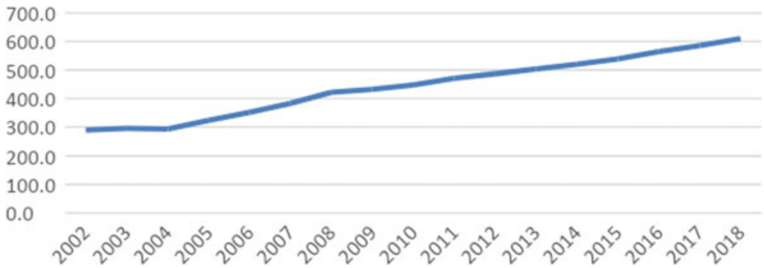

Fig. 12 Number of cars per 1000 inhabitants in Poland

households have more than two vehicles. The result of Warsaw is partly surprising—despite the difficult traffic conditions and good public transport offer, the attachment to individual car transport is still strong and very noticeable.

Figure 13 shows the structure of automobiles according to the engines used. This structure of vehicles owned by respondents according to propulsion type is dominated

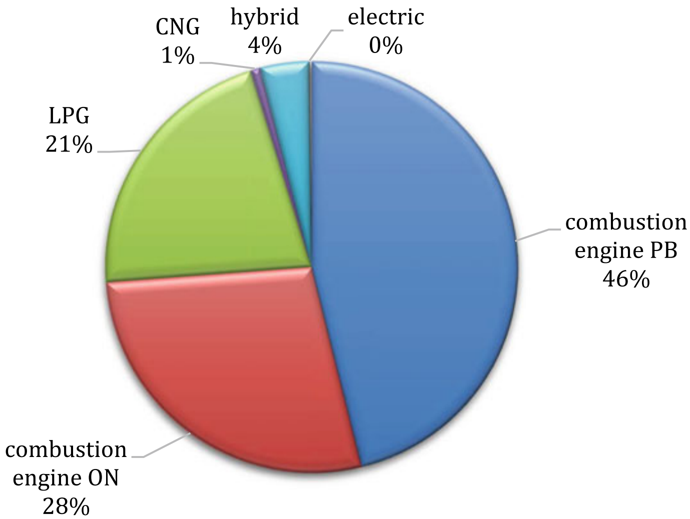

Fig. 13 Structure of car engines of the respondents

Table 7 Number of two-wheeled vehicles in households of the respondents

Data range	No two-wheeled vehicle (%)	1 vehicle (%)	2 vehicles (%)	3 vehicles and more (%)
Overall	32.2	37.8	19.8	6.9
Warsaw	31.3	44.7	18.0	3.3
Tricity	30.0	46.0	20.7	2.7
Silesia metropolis	35.3	22.7	20.7	14.7

by combustion engines: petrol (46%) and diesel (28%). The third group in number is vehicles with LPG gas installation. Low-carbon vehicles with hybrid or electric propulsion are not very popular among the respondents. The possession of 20 hybrid cars and only 1 electric car was declared among the entire examined group.

The respondents were also asked about the two-wheeled vehicles (Table 7): in the case of Warsaw and Tricity approximately 30% of households do not have a two-wheeled vehicle, whereas 44–46% of households have one such vehicle. A totally different structure exists in Silesia Metropolis, where, on the one hand, the highest percentage of households without a two-wheeled vehicle was recorded, and on the other hand, as much as 21.4% of respondents declared the possession of 3 or more vehicles. A probable factor having impact on this solution is the above-mentioned distances in the area of Silesia Metropolis, resulting from a lower concentration of workplaces, administration, universities and schools. It is also possible that *sharing economy* solutions related to two-wheeled vehicles, which are less developed in Silesia Metropolis, have an impact in this respect.

The structure of two-wheeled vehicles (Fig. 14) is dominated by traditional bike classic scooters and electric scooters. Probably some of these devices are not used directly by the representatives of the creative class, but also by their family members (especially children). In the case of direct use, the respondents most frequently mentioned traditional bike, and the largest percentage of respondents declared that they

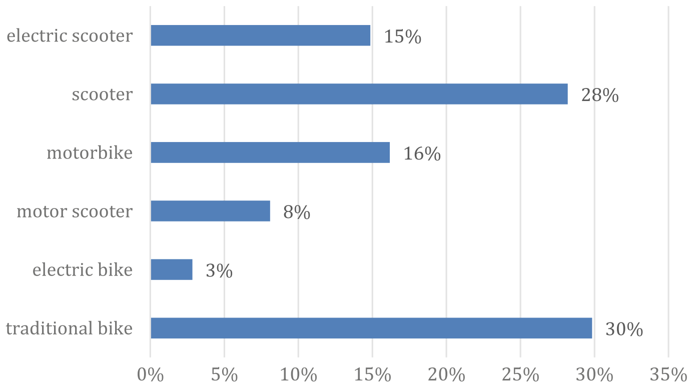

Fig. 14 Structure of two-wheeled vehicles owned by the respondents

normally used it less often than once a week—which indicates the mainly recreational use of bikes.

The respondents were also asked to prepare a travel diary for the latest working day, excluding Mondays and Fridays. Based on the presented photograph of the working day, the journeys made by the respondents can be very well parameterised and their main transport behaviours can be distinguished. It was adopted that a journey is every time connected with specific motivation, which results from the secondary character of transport needs. On the other hand, each journey consists of specific rides, or more precisely speaking, movements. Movements may result from the journey complexity, e.g. transfers, changes of the transport mode, etc.

According to Table 8, the biggest number of journeys per day was executed on the average by people working in Silesia Metropolis, whereas the biggest number of movements were made by people working in Warsaw. The journey model (Fig. 15)

Table 8 Number of journeys made by the respondents (photograph of the working day)

Data range	Number of movements per day	Number of journeys per day	Average number of movements per day	Average number of journeys per day
Overall	1212	1044	2.69	2.32
Warsaw	445	351	2.97	2.34
Tricity	371	326	2.47	2.17
Silesia metropolis	396	367	2.64	2.45

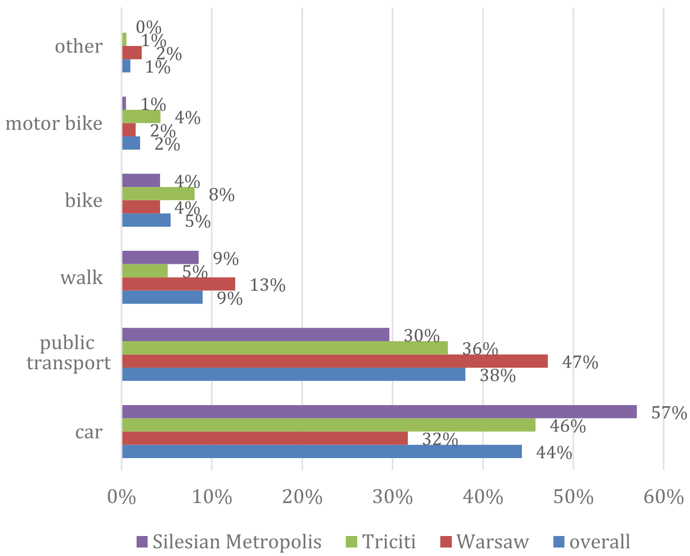

Fig. 15 Journey modal split of the creative class

Table 9 Distance of journeys made by the respondents

Data range	Total distance travelled per day (km)	Average travel distance (km)	Average daily distance of the respondent (km)
Overall	12,109	11.60	26.91
Warsaw	3345	9.53	22.30
Tricity	3711	11.38	24.74
Silesia metropolis	5053	13.77	33.69

looked very similar every time, regardless of the area. Due to the fact that adult working people were examined, the basic motivation pattern took the following form: home—work—home. On the return from work, there were sometimes additional motivations related to: micro shopping, shopping in shopping centres or leisure and entertainment. Based on the obtained data, the journeys made were parameterised according to the distance travelled (Table 9). The results showed that the longest journeys were definitely made by representatives of the creative class from Silesia Metropolis, whereas the shortest distance of movements was recorded in Warsaw.

Based on the results, the modal division of respondent journeys was prepared, taking into account the mode of movement used. Overall, the car dominated, the second position went to public transport, whereas the third position went to pedestrian movement and the fourth to the bike. The obtained results were different from one other in specific locations, and the advantage of public transport in fulfilling transport needs of the creative class was particularly visible in Warsaw. It is also worth emphasizing the unfavourable structure of division of tasks in Silesia Metropolis, with clear domination of individual transport and the lowest use of public transport.

The respondents were asked to choose the key postulate that guides them in selecting the mode of transport, or more broadly speaking, the mode of travel (Table 10). Overall, the first place went to cost and the second one went to comfort, followed by travel time, directness and safety. A different hierarchy of transport postulates resulted from the research in Silesia Metropolis, where the most important factor was travel time.

Table 10 The most important factors influencing the choice of movement mode according to the respondents

Data range	Travel time (%)	Comfort (%)	Cost (%)	Directness of travel (%)	Safety (%)	Other (%)
Overall	22.4	26.9	28.4	18.0	2.4	1.8
Warsaw	22.7	24.0	38.0	11.3	2.7	1.3
Tricity	5.3	30.7	37.3	22.0	4.7	0.0
Silesia metropolis	39.3	26.0	10.0	20.7	0.0	4.0

The following question concerned what would make the respondent use public transport instead of passenger car (Table 11). The largest percentage of respondents indicated that the reduction of public transport ticket prices would be the encouraging factor. The following among the most frequently indicated answers concerned the physical improvement of transport offer by: increase of transport frequency, development of network of connections and correction of the layout of transport stops.

Another group of questions concerned the possibility of increasing the share of the bike in fulfilling the transport needs of inhabitants. Based on the analysis of the data from Table 16, it may be noticed that more emphasis is placed on the comfort of using the bike in commuting to work. In Warsaw and Tricity, the expectations regarding bike routes have already been partly fulfilled. The problem of the lack of bike paths dominates in the Silesian Metropolitan Union area, which results e.g. from a huge dispersal and lack of integration of particular parts of the network of bike paths in the whole metropolis system. An increasing emphasis from the respondents is placed on the comfort of bike use in commuting to work, and overall, as many as 26.3% respondents indicated that the possibility to leave the bike in a safe place of travel destination was most important (Table 12).

Bike is a mode of transport whose use is undoubtedly affected by the atmospheric conditions. The results presented in Table 13 indicate that regardless of the weather conditions, bike is overall used in daily journeys by 6.8% of respondents. Tricity clearly stands out in this aspect, with the index exceeding 12%. However, it does not change the fact that the use of bike as the basic mode of transport is strictly dependent on the weather conditions, and on the average, 71.7% of the respondents use the bike only in the case of good weather.

Another group of results presents the feelings and intentions of the respondents concerning the use of passenger cars. The goal in this case was to identify the potential of changes from combustion cars to low-carbon or zero-emission vehicles. According to the data from Table 14, the respondents are definitely not going to replace their combustion car with an electric or hybrid car. The results show that the respondents are very sceptical about the problem of purchasing low-carbon vehicles. While particularly low interest is shown in the purchase of electric car, the respondents are more enthusiastic about hybrid vehicles, but mainly about their classic version. The respondents are most likely concerned about:

- high cost of purchasing electric vehicles,
- concerns regarding the evolution of operating costs in a longer time perspective,
- insufficient charging infrastructure.

Positive motivations for the replacement of combustion vehicle with a hybrid or electric car are focused on two issues: lower operating costs and better environmental effect. In the case of Warsaw, ecological motivations are more frequently expressed than the economic ones. (Table 15)

The respondents were asked to refer to the proposals of different variants of restricting passenger car traffic in city centres. To each of the presented statements, the respondents could answer based on five-point Likert scale, from "I definitely

Table 11 Factors encouraging the withdrawal from individual transport in favour of public transport according to the respondents

Data range	Ticket price reduction (%)	Higher transport frequency	Building P&R parks (%)	More convenient location of transport stops	Increasing comfort (%)	Development of network of connections (%)	Building transfer nodes (%)	Other (%)	Nothing will convince me (%)
Overall	22.9	19.0	8.2	11.0	12.5	15.8	7.1	1.4	2.1
Warsaw	25.4	18.8	6.9	12.2	12.4	15.2	8.1	0.3	0.8
Tricity	13.6	14.6	13.9	15.2	17.4	14.2	8.5	0.0	2.5
Silesia metropolis	28.9	23.6	4.3	5.6	7.8	18.0	4.3	4.0	3.4

Table 12 Identification of the main factors encouraging the respondents to make bike journeys on a daily basis

Data range	Roofed parking facility (%)	Availability of bike paths (%)	Availability of B&R parks (%)	Possibility to leave the bike in a safe place in the destination area (%)	Other (%)	Nothing will convince me (%)
Overall	12.4	23.4	20.2	26.3	0.8	16.8
Warsaw	15.2	18.2	21.2	26.9	1.5	17.0
Tricity	14.7	20.2	26.0	29.8	0.8	8.5
Silesia metropolis	6.6	33.2	12.4	21.7	0.0	26.1

Table 13 Use of bike by respondents depending on the weather conditions

Data range	Regardless of the weather conditions, also in the winter (%)	Regardless of the weather conditions, except for the winter (%)	Only in the case of good weather (%)
Overall	6.8	21.5	71.7
Warsaw	3.6	27.5	68.8
Tricity	12.5	25.0	62.5
Silesia metropolis	3.9	10.9	85.2

Table 14 Plans of respondents concerning the replacement of combustion car with electric of hybrid car

Data range	I'm not going to replace the car (%)	Electric car (%)	Hybrid plug-in (%)	Hybrid (%)
Overall	70.8	4.9	7.2	17.1
Warsaw	69.7	7.6	5.5	17.2
Tricity	67.6	5.8	13.7	12.9
Silesia metropolis	75.0	1.4	2.7	20.9

Table 15 Structure of motivation for the purchase of electric/hybrid cars by the respondents

Data range	Expected financial support of the purchase (%)	Easier access to the city centre (%)	Lower operating costs (%)	Better environmental effect (%)
Overall	13.4	12.8	36.3	37.4
Warsaw	18.3	3.3	36.7	41.7
Tricity	9.4	28.1	35.9	26.6
Silesia metropolis	12.7	5.5	36.4	45.5

don't agree" to "I definitely agree". The results were aggregated in three types of attitudes to the recorded statements: positive, negative and lack of opinion. The results presented in Table 16 indicate that the representatives of the creative class are willing to accept restrictions in passenger car access to city centres. A necessary element to build the approval for such solutions is to offer something instead. The respondents were most positive about the solutions ensuring the possibility of quick access to the city centre by public transport and in the case of high availability of public transport. The responses indicate the reluctance of respondents to use modern solutions, e.g. sharing economy and e-mobility.

5 Summary

The development of sustainable urban mobility requires a change of transport behaviours of the inhabitants, which will lead to effective and environmentally-friendly functioning of cities. Representatives of the creative class are an important social group, which is by assumption characterised by open-mindedness, ecological awareness and progressive thinking. This group has a strong opinion-forming voice and is indicated as the driving factor behind the regional development. Due to this, the transport behaviours and postulates of the creative class became a research object for the authors of this chapter.

The main conclusions drawn from the conducted study are as follows:

1. Representatives of the creative class execute a high number of journeys, among which car transport dominates.
2. Cars with conventional engines dominate in the households.
3. Contrary to the original claim, the creative class pays attention to the cost-related aspect of particular solutions.
4. In the group of factors influencing the possibility to withdraw from individual transport, the belief in required development of public transport dominates, whereas the respondents are largely sceptical about modern solutions resulting from the implementation of e-mobility and sharing economy.
6. The creative class is environmentally conscious and notices the possibility to reduce the external costs of transport. It means that this class can be a significant actor in the development of sustainable mobility.
7. Bike transport has a large and unused potential to influence a change of transport behaviours.

On the average, representatives of the creative class execute approximately 2.32 journeys per working day. The detailed comparisons indicated that the index of daily number of journeys for the creative class is higher than the average number for all inhabitants in each metropolis. The distribution of transport tasks in the creative class is similar as in the specific locations. Outside Warsaw, passenger car dominates in the movements of the creative class. Car is present in a majority of the analysed households. A low percentage of alternative-powered vehicles, especially hybrid and

Table 16 Opinions of the respondents concerning the limitation of passenger car traffic in the city centres

Statement	Negative attitude (%)	No opinion (%)	Positive attitude (%)
Entrance of passenger cars to the city centre should be restricted (e.g. by introducing tolls, prohibition to enter during peak hours, etc.)	38.0	18.9	43.1
I accept the restriction of car access to the strict city centre if it is possible to travel shorter by public transport	24.2	20.9	54.9
I accept the restriction of car access to the strict city centre if the public transport price is low	24.9	24.2	50.9
I accept the restriction of car access to the strict city centre if the public transport is highly available (short walking distance to the public transport stop)	22.7	23.8	53.6
I accept the restriction of car access to the strict city centre if public transport ensures direct connection with the city centre	21.6	28.0	50.4
I accept the restriction of car access to the strict city centre if it is possible to travel by bike	28.9	32.9	38.2
I accept the restriction of car access to the strict city centre if car sharing—payable short-term car rental system, e.g. Traficar is developed (cars within this system can enter the city centre)	29.1	38.4	32.4
I accept the restriction of car access to the strict city centre if it is possible to travel by other modes of transport within a payable short-term car rental system (e.g. electric scooters)	33.3	28.4	38.2

electric vehicles, is noticeable. Additionally, a vast majority of the respondents are unwilling to replace combustion vehicles with low-emission vehicles. A significant factor preventing the replacement of vehicles is the high cost of purchase and uncertainty regarding the operating costs. The key barrier for the selection of electric or hybrid car as the next individual vehicle is the income barrier.

Car is the main method for fulfilling transport needs. Therefore, it may be concluded that the indicated key postulates related to the selection of the mode of transport are precisely applicable for the car. These are: travel comfort and cost. Travel time is the decisive factor behind the selection of the mode of transport in the case of Silesian Metropolis, comfort dominates in Tricity, whereas cost is the priority in Warsaw, followed by Tricity. While in the Upper Silesian Metropolis the cost is less important, in the case of Warsaw and Tricity it seems to be a more significant factor behind the selection of the mode of transport. This does not change the fact that far more than a half of the choices concern travel time and comfort, and since the dominating mode of transport is car, it may be recognised that it is precisely travel comfort and time that decide about the choice of car as the basic method for travelling in metropolises. Therefore, it may be concluded that the role of car in fulfilling mobility mainly results from the fact of shorter travel time and higher comfort offered by car.

A change of transport behaviours is very difficult. The respondents, when asked about the factors that would make them use public transport and withdraw from the use of cars, were sceptical about the restrictive instruments (limited parking time for vehicles in city centres, restriction in vehicle access to the city centre and high parking fees). When asked what would make them resign from individual transport and change to public transport in daily journeys, the respondents indicated the key importance of reduction of ticket prices, whereas the quality of transport understood as ensuring a higher frequency of public transport, as well as its comfort and availability, were stated much more frequently. There were noticeable differences between the metropolises resulting from the development status of public transport in such urban areas. In particular, higher significance in Silesia Metropolis was attached to price reduction and increase of availability. It is also worth noting the higher acceptance of respondents for the instruments which, although restricting the car access, are still related to positive actions, especially such as: short time, high availability and low public transport price. However, this does not apply to all positive tools—the respondents keep distance to the substitutive role of car sharing and sharing economy-based system of scooters.

The creative class notices the problem of ecology in their responses. Despite being sceptical about electromobility, they also appreciate the ecological benefits of electric car and lower operating costs, whereas they are more reserved about the transport policy instruments that would enable to subsidise the purchase of car and use it easier in the urban space.

Although the use of bike in daily journeys (based on the travel diary) is declared by 5% of respondents on the average, the occasional and mainly recreational use of bikes probably dominates, because only 6.8% of the respondents reported all-year bike activity, insensitive to weather changes, whereas over 70% of respondents use the bike only in good weather. Among the barriers preventing the popularisation of transport function of bikes, the respondents mentioned the deficiencies in linear infrastructure and shortage of adequate parking lots in the destination areas.

The right to move is one of the fundamental citizen rights and freedoms. Due to this, it is very difficult to cause a change of transport behaviours. The research results indicate that the instruments for sustainable mobility based on innovations do not entirely meet the expectations. The largest potential for a change of behaviours still lies in the development of public transport offer and creation of good conditions for bike movements.

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Research on the State of Urban Passenger Mobility in Bulgaria and Prospects for Using Low Carbon Energy for Transport

Velizara Pencheva, Asen Asenov, Ivan Georgiev and Aleksander Sładkowski

Abstract The work investigates the state of and the challenges facing the urban mobility in Bulgaria, related to demographic problems, the operation of urban public transport, the environment and traffic safety. Four stages in the evolution of urban mobility in the country in the second half of the 20th century have been reviewed and a study on the 12 plans for sustainable urban mobility (SUMP) developed by 2019 has been presented. The issues of building a sustainable transport system in the cities through engineering and technological solutions for decarbonisation of transport, shared integrated mobility, as well as servitisation of transport in the cities have been discussed. Some technological solutions for the use of electrical, hybrid and hydrogen fuel cell powered vehicles, including prototypes developed by high school and university student teams have been presented. Research on energy consumption for a river vessel, powered by solar panels has been reported. On the basis of two criteria—for the shortest time and the least harmful emissions, a multicriterial optimisation of public transport travels has been developed. Using Matlab, a programme solving the task of the model defined has been implemented. The input data are the adjacent matrices and the number of pseudorandom Sobolev probing points. Pareto-optimal discrete solutions have been defined, providing the opportunity for the decision-maker to choose one.

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1 State and Challenges Facing Urban Mobility in the Republic of Bulgaria

1.1 Urban Mobility

Mobility is defined as the ability to meet the needs of society to move freely, to gain access, to communicate, to trade and establish relationships. Sustainable mobility means to do all this without sacrificing other human or ecological values today or in the future [1]. In other words, the concept for sustainable mobility assumes that all citizens can choose options for accessibility and mobility, which are safe, convenient, timely and affordable and, at the same time, have high levels of energy efficiency and reduced environmental impact. The term "sustainable mobility" is related to the term "sustainable transport", which is a logical continuation to the term "sustainable development".

The dimensions of urban mobility are shown in Fig. 1.

The environmental dimension assesses the reduction of the harmful impact of transport in cities, lowering of harmful emissions and noise, reducing the public space taken by automobiles.

The social dimension includes indicators that reflect the number of people to be served by the urban transport system more conveniently and fairly.

The economic dimension fixes the increase of the investment attractiveness of transport infrastructure or objects in it.

The institutional dimension of mobility means strengthening the authority of local and state governments on the basis of well-founded decisions in the field of mobility.

The mobility processes are governed by personal preferences, as well as by the physical and financial capacities of individuals when selecting a mode of travel.

Providing sustainable urban mobility is a complex process, associated with high costs and adverse impacts:

- energy consumption and climate change:

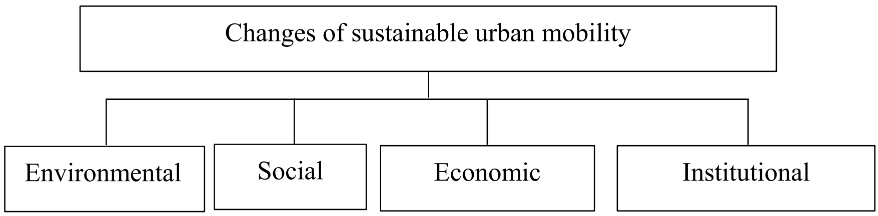


Fig. 1 Changes of sustainable urban mobility

  - greenhouse effect;
  - energy dependence of transport on liquid fuels.

- harmful effects on the environment and human health:

  - atmospheric and noise pollution;
  - road accidents.

- traffic and congestion in the cities;
- uneven growth of different types of urban transport:

  - a large share of the personal vehicles used for transport;
  - a large share of urban space is needed for movement and parking of vehicles;
  - limited space for pedestrians and cyclists;
  - necessity to improve the integration between the use of urban space and transport planning.

The costs for mobility include a number of indicators such as:

- investments for transport infrastructure;
- investments in transport vehicles;
- investments in traffic and communications management;
- expenses for organisation of transportation and ensuring road safety;
- running costs for operating vehicles and communications;
- fuel and electricity costs;
- costs needed by society to cover losses from accidents, noise and harmful effects in the atmosphere, etc.

In Bulgaria there is no practice and methodology developed for assessing the price of mobility. There exist different subsidies from municipal and state sources. Official statistics is kept for the numbers of people killed and injured in accidents, but there is no precise estimation of those who die prematurely due to pollution, caused by transport or illnesses related to the sedentary way of life and insufficient physical activity.

The trends observed in the last 8–10 years show that in the next period, the mode of transport in cities will undergo drastic changes. The advancement in technology and the new transport services will allow citizens to move through the city in a more and more efficient and safe way. These changes may have profound economic and social effects.

1.2 Challenges Facing Urban Mobility in Bulgaria

Today, a number of challenges can be outlined, regarding urban mobility, among them: population aging and urbanization processes; state of public urban transport and its operation; environmental pollution; traffic congestion and safety.

1.2.1 Demographic Tendencies in the Country, Related to Population Aging and Urbanization Processes

The Urban population numbers are one of the prime indicators for their development and for economic potential and the consumer needs of the population. It is an essential indicator in the planning of technical and social infrastructure, including transport services to the population.

The increase in population concentration in large cities is a fact, which should be observed because it requires certain measures to ensure living conditions, including transport. In 2018, the urban population in Bulgaria amounts to 5,159,129, which is 73.5% of the whole population.

Approximately 70% of this population is in the regional centres—27 cities (Table 1). Six of them have population of over 100,000. By 31.12.2018, Sofia has a population of 1,241,675, which is almost twice as many as the population of Plovdiv and Varna together (the second and third largest cities). The population of Sofia is almost 25% of all the urban population of Bulgaria. The imbalance of the territorial distribution of the population is deepening [2].

With the domestic migration (for 2017), the largest territorial movement is towards the cities, where “city to city” migration is 42.3%, followed by “village to city” at 24.2%. The biggest share of migrants in the country have chosen the capital—Sofia (a total of 18,286 people).

At the same time, a continuing aging is observed, including in the cities, with about 1/5 of people at 65+ (Fig. 2). In 2010, the population of 65+ in the cities was under 15%, while in 2019 it is already almost 20% of all the population.

Table 1 Population in regional city centres in the country, 2018

Regional city centre	Population	Regional city centre	Population
Sofia	1,241,675	Pazardjik	68,194
Plovdiv	346,893	Yambol	68,074
Varna	336,505	Vratsa	52,617
Burgas	202,434	Gabrovo	52,169
Ruse	142,902	Kurdjali	43,263
Stara Zagora	135,715	Vidin	41,583
Pleven	96,610	Kyustendil	39,881
Sliven	86,275	Montana	39,240
Dobrich	83,584	Targovishte	35,453
Shumen	75,500	Lovech	32,363
Pernik	73,111	Silistra	31,468
Haskovo	70,406	Razgrad	30,575
Blagoevgrad	69,178	Smolyan	27,505
Veliko Tarnovo	68,859	Total	3,592,032

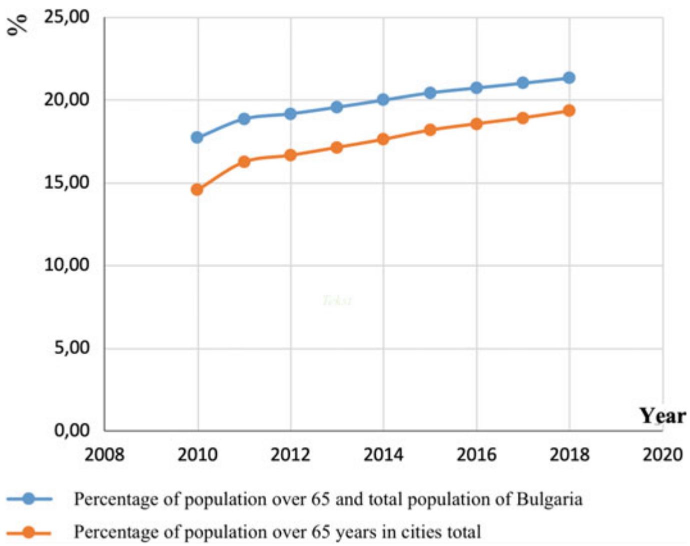


Fig. 2 Percentage of population over 65 and the total number of population in Bulgaria for the country and the cities

Trends in the general demographic indicator "population" testify that the quantitative growth of cities and especially of the capital is a factor, which will be preserved in future. Another tendency is the continuous aging of the population in the country, and particularly in the cities. It should be noted, however that this does not always correlate with the quality changes in urban environment and living conditions.

1.2.2 Volume of Transport Operations of Public Urban Passenger Transport in Bulgaria

Public urban passenger transport in Bulgaria is part of the county's unified transport system and an integral part of the city infrastructure. It is carried out by buses, trolleybuses, trams and underground (only in the capital). The volume of transport operations measured in numbers of passengers served and in pkm by modes of transport is shown in Table 2. Bus transport has the largest volume of transport operations with 346,550,000 passengers served and 3131 million pkm for 2017. In many cities it plays an important role in passenger service. The percentage of passengers served by modes of public transport is shown in Fig. 3, with bus transport serving more than half of the passengers (55%), followed by trams with 18%, underground—15% and trolleybuses—12%.

From Table 2 we can see the average transport distance for each mode of transport, noting its increase over the period reviewed. The average transport distance for all modes of transport in 2008 was 6.35 km while in 2017 it was 7.29, i.e. there is an increase of over 1 km.

Table 2 Volume of transport operations by modes of urban transport

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Bus transport										
Number of passengers served, thousand	448,530	424,134	412,447	383,839	390,235	325,965	330,001	339,769	371,711	346,550
Transport operations completed, million pkm	3737	3519	3572	3328	3370	2790	3184	3122	3201	3131
Average transport distance, km	8.33	8.30	8.66	8.67	8.64	8.56	9.65	9.19	8.61	9.03
Tram transport										
Number of passengers served, thousand	133,869	126,999	121,498	120,139	119,901	105,554	95,348	90,193	88,504	110,906
Transport operations completed, million pkm	249	225	213	209	262	317	300	292	285	283

(continued)

Table 2 (continued)

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Average transport distance, km	1.86	1.77	1.75	1.74	2.19	3.00	3.15	3.24	3.22	2.55
Trolleybus transport										
Number of passengers served, thousand	137,050	116,413	197,849	101,290	101,416	84,546	75,328	70,011	66,732	77,682
Transport operations completed, million pkm	590	485	445	404	410	365	336	317	306	342
Average transport distance, km	4.30	4.17	2.25	3.99	4.04	4.32	4.46	4.53	4.59	4.40
Underground										
Number of passengers served, thousand	28,181	42,840	61,820	58,752	64,542	79,348	83,912	87,877	89,666	91,066

(continued)

Table 2 (continued)

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Transport operations completed, million pkm	169	388	618	587	737	761	503	527	606	808
Average transport distance, km	6.00	9.06	10.0	9.99	11.4	9.59	5.99	6.00	6.76	8.87
Total										
Number of passengers served, thousand	747,630	710,386	793,614	664,020	676,094	595,413	584,589	587,850	616,613	626,204
Transport operations completed, million pkm	4745	4617	4848	4528	4779	4233	4323	4258	4398	4564
Average transport distance, km	6.35	6.50	6.11	6.82	7.07	7.11	7.39	7.24	7.13	7.29

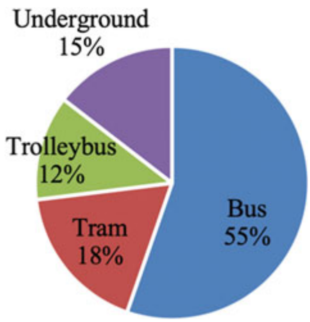


Fig. 3 Percentage of passengers served by modes of public transport

Due to the performance characteristics of different modes of transport, as well as the organisation of operations, the average distance (for the period 2008–2017), i.e. the average distance each passenger has travelled, differs significantly for the different modes of transport. In Table 3, its main number characteristics are shown. The lowest value of the average distance in this period is for the tram transport—2.45 km (Table 3), followed by the nearly twice as high value for the trolleybus transport—4.10 km. For the underground and trolleybus transport the average distance is almost the same—8.37 km and 8.76 km, respectively.

Data on the number of vehicles, length of routes, passenger seats, etc. for five years from 2013 to 2017 are shown in Table 4. The length of urban bus, tram, and trolleybus networks decreased in the given period; only the length of metro lines increased. The cities using trolleybus transport also decreased from 13 to 10 in the period reviewed.

The urban public passenger transport is an important element of the unified transport system of the country since it provides for-work and other types of travel on

Table 3 Main number characteristics of the average distance by modes of transport

	Bus	Tram	Trolleybus	Underground
Mean	8.76	2.45	4.10	8.37
Standard error	0.13	0.21	0.22	0.63
Median	8.65	2.37	4.31	8.96
Standard deviation	0.41	0.66	0.68	2.01
Sample variance	0.17	0.43	0.46	4.03
Kurtosis	1.13	−2.12	7.79	−1.59
Skewness	1.16	0.13	−2.69	−0.08
Range	1.35	1.50	2.34	5.42
Minimum	8.30	1.74	2.25	5.99
Maximum	9.65	3.24	4.59	11.42
Sum	87.64	24.47	41.05	83.67
Count	10.00	10.00	10.00	10.00

Table 4 Number of vehicles, passenger seats, route length 2013–2017

Year	2013	2014	2015	2016	2017
Bus transport					
Number of bus lines	650	643	636	700	565
Length of urban bus network, thousand km	7.0	7.0	6.8	6.4	6.4
Tram transport					
Length of urban bus network, km	146	146	146	137	137
Number of trams	280	285	280	280	311
Passenger seats, number	59,548	60,348	59,078	56,618	62,958
Trolleybus transport					
Cities with trolleybus transport, number	13	13	12	10	10
Route length, km	483	491	454	408	400
Trolleybuses, number	467	563	540	437	392
Passenger seats, number	51,529	62,978	60,429	48,708	43,868
Underground					
Length of metro lines, km	29	29	37	38	38
Trains, number	208	208	208	208	208
Seats	64,064	64,064	64,064	64,064	64,064
Range in thousand km	3389	3398	4301	4544	4541

the territory of the city, which are more efficient than using private automobiles. Not only the people, but also the municipalities and the state in general are interested in its appropriate functioning. It also has a significant impact on the economic and social development of a certain place.

1.2.3 Challenges for the Environment

Transport has a serious impact on all components of the environment. Air pollution from transport leads to considerable health hazards. Some of the effects, resulting from transport-caused pollution become visible only after a long period and have global impact, no matter where the emissions have been generated.

It is an indisputable fact that the increase in the numbers of automobiles in the country and their concentration in the cities, the outdated transport fleet, including that of public transport, leads to a considerable increase in the emissions of greenhouse gases into the atmosphere, noise pollution, traffic congestions and insufficient parking space, accidents, etc.

Greenhouse gas emissions account for the impact on global warming. The indicator "greenhouse gas emissions" consists of emissions from six greenhouse gases, confirmed and included into "the Kiyoto basket": of them carbon dioxide (CO_2) is the cause for 50% of the global warming.

Table 5 Emissions of harmful substances from transport in the period 2011–2017 in tonnes

Pollutants	2011	2012	2013	2014	2015	2016	2017
Sulphur oxides (SOx)	124	126	99	107	37	38	39
Nitrogen oxides (NOx)	40,145	41,645	36,002	38,833	45,407	47,196	39,856
Non-methane volatile organic compounds (NMVOC)	14,884	14,922	12,889	12,822	13,468	11,522	9442
Methane (CH_4)	4183	5010	4811	5720	7137	8253	9672
Carbon oxide (CO)	82,023	76,448	65,258	70,642	72,396	67,860	60,367
Carbon dioxide (CO_2)	7,492,696	7,822,405	6,830,455	7,849,870	8,651,578	8,767,523	8,842,106
Dual nitrogen oxide (N_2O)	211	222	201	231	268	268	272
Ammonia (NH_3)	741	739	772	901	959	900	829

In Table 5, data on the emissions of harmful substances from transport in the period 2011–2017 in tonnes are included.

From the table it can be seen that CO_2 was continuingly increasing during the period. For 7 years it has grown by 18%, which as average annual increase is 0.81%. In 2017, the carbon dioxide emissions from road transport were 8,842,106 t. Of the remaining harmful substances, for the same period—2011 to 2017—the methane increased almost twice, and so did dual nitrogen oxide and ammonia.

The dust and fine particle concentration in the cities, caused by domestic burning and industry, as well as by heavy traffic, is often above limits.

The noise caused by transport depends directly on the traffic intensity, the speed and structure of transport flow, the age of the transport fleet, the type and quality of infrastructure, the situational and level position of the road and the nature of the terrain and on both sides. The adverse trends of the factors, affecting the acoustic environment are confirmed by the noise characteristics of cities. They show a persistent tendency to increase noise pollution in urban territories to levels in the range of 63–67 and 68–72 dB(A), while the norm is 55–60 dB(A). In Sofia, in 2018, in more than two-thirds of the points of noise measurement, the noise level exceeded the limit values to varying degrees, but no noise levels in the range of 78–82 dB(A) were registered and this trend is sustainable. Noise level in 84% of the points in territories with intensive traffic and tram and rail transport is above the limit values [3].

1.2.4 Road Traffic Loading and Safety

Sofia is 52nd among the most congested cities for 2018 (from 403 cities in 56 countries on 6 continents). According to TomTom Traffic Index, the travel time in Sofia for 2018 and 2017 is extended by an average of 35%.

The steady increase of automobiles in cities poses serious problems with parking and limits urban living space.

There is a considerable number of accidents in the cities in Bulgaria. The total number for 2017 is 6888, of which 4426 were in cities (64.25%). From a total of 682 killed in accidents in 2017, 200 were killed in cities, i.e. about 30%.

The above-mentioned fully justifies the need for solving the issues for efficient operation of urban passenger transport by reducing the load of traffic in cities as one possible solution [4, 5].

Nowadays, the market for public urban passenger transport services is represented by municipal enterprises and by private carriers. In some cities they operate together along the network of routes. Through their structures and measures, municipalities create the needed mechanism, which allows managing the entire system of public passenger transport on the territory of a given city.

1.3 Evolution of Urban Mobility in the Country

The development of urban mobility in the second half of the 20th century in Bulgaria goes through four major stages:

- stage 1—characterised by an interest in increasing automobile ownership and expanding the transport infrastructure of cities;
- stage 2—stimulating the use of public transport, at the expense of reducing automobile use and securing infrastructure for this;
- stage 3—a sharp increase in the number of private automobiles, most of which are too old and thus, increasing the automobile traffic load in cities;
- stage 4—promoting sustainable travel and alternative forms of travelling in cities.

Evidence of the presence of these four stages is the changing number of automobiles in the cities—from a considerable increase to stable numbers, as well as the constant development and improvement of public passenger transport, together with the development of alternative types of transport and modes of travelling.

The evolution of mobility in all western European countries is characterized by stages 1, 2 and 4, while stage 3 is characteristic for the countries from Central and Eastern Europe.

After Bulgaria's accession to the European Union in 2007, a lot of efforts have been made in compliance with the European standards for modern, eco-friendly and safe transport system. Measures have been taken to harmonise the Bulgarian legislation with the European conditions for changes of ownership in the transport sector, which can lead to improving the quality of services.

During the first programme period (2007–2013) the state policy was focused mainly on infrastructure measures and, to a lesser degree, on issues of mobility management. Under Operative programme Transport 2007–2013, predominantly financed by the European Regional Development Fund (ERDF) and the EU Cohesion Fund (CF) with local co-financing, a large-scale “Project for expanding the underground in Sofia” started. Since 2007, the development of urban mobility has been managed by the implementation of several EU projects at municipal, regional and national level. In the Strategy for development of the transport sector by 2020, was included the development of integrated plans for urban transport through Operative programme Regional Development for the seven largest cities in Bulgaria—Sofia, Plovdiv, Varna, Burgas, Ruse, Stara Zagora and Pleven. The aim is to develop sustainable environmentally-friendly transport systems. This requires creating conditions for increasing the number of passengers, using public transport, as well as developing programmes for building bicycle paths and parking places, etc.

Sustainable urban transport development is included as Priority 8 in Operative programme Transport 2014–2020. During this period the construction of the underground in Sofia is continuing with the building of a section of the third and last metrodiameter, which will be completed in the next programme period 2020–2027.

2 Plans for Sustainable Urban Mobility in Bulgaria

2.1 A Concept for Sustainable Urban Mobility Planning (SUMP)

In 2013, the European Commission published its Urban mobility package. The focus of this document is the energy efficiency of transport and the climate changes. The concept for Urban Mobility Plans (SUMP) is included in this package [6].

The concept for sustainable urban mobility is still new in Bulgaria and the development of SUMP is not required by law. In Bulgaria, the transport schemes in cities are regulated by the Road transport Act. The municipalities are responsible for the policy and decision-making, related to spatial and urban planning and development of municipal territory.

In the national programme of reforms in Bulgaria 2011–2015, the development and implementation of sustainable urban mobility plans (SUMP) was planned for 35 municipalities by the end of 2015, which has not been achieved.

The developing and implementation of SUMP is the initiative of individual municipalities. The developing of the concept is a transition from the traditional planning of migration of people to the cities, oriented predominantly towards developing the infrastructure and planning of sustainable urban mobility, directed to meeting the needs of different groups of people.

The main elements of the concept for sustainable urban mobility (SUMP) are shown in Fig. 4.

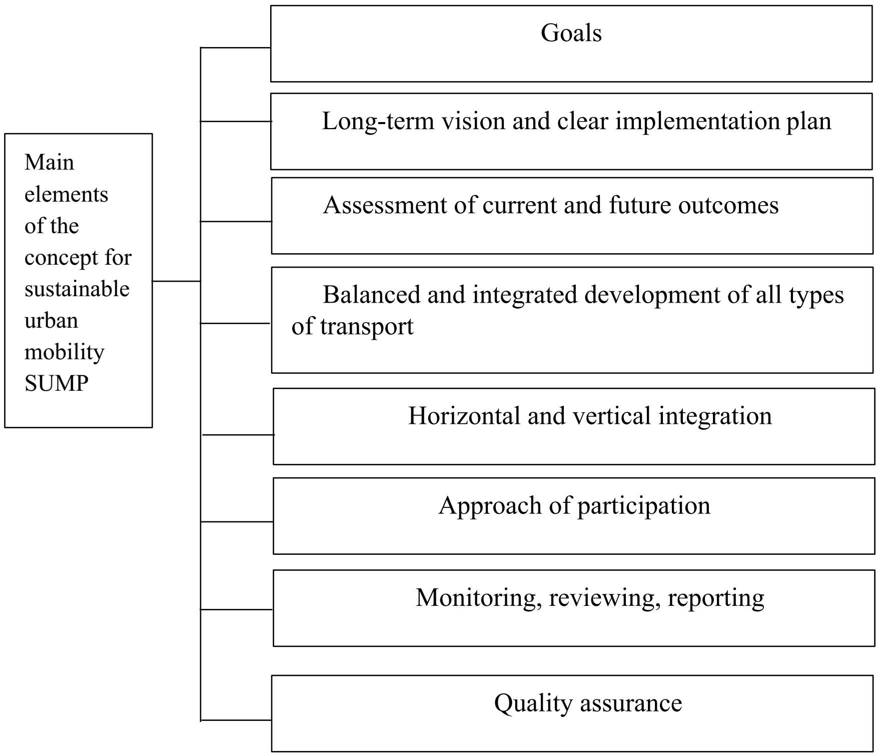


Fig. 4 Structural scheme of the concept for sustainable urban development SUMP

Three important moments can be identified, which distinguish the approach to sustainable urban mobility in comparison to the traditional one.

First, the plans for sustainable urban mobility SUMP are oriented to all possible modes of travelling in the city, including public transport (bus, trolleybus, tram, underground, taxi), personal automobiles, bicycles, walking. In the conditions of our country, as well as in many other cities in the world, it means using these modes of travelling, which will provide quality mobility and reduce the effects of transport on the environment. In practice, it implies quality and energy efficient public transport, creating favourable conditions for cycling and walking and gradual phasing out the use of personal automobiles as a main means for travelling in cities.

Secondly, an important characteristic of the tool, used for planning the sustainable urban mobility is the active inclusion in the discussions and the decision-making process with the stakeholders and the general public. This makes it possible to take into account the various needs of the population groups.

The third most significant difference in planning the sustainable urban mobility, compared to the traditional approach is the assessment of the results, which are directed t re-orientation from development of infrastructure (roads, bus stations, transport vehicles, etc.) to priority activities, providing customer satisfaction.

Accordingly, when preparing ban mobility plans, target indicators such as percent of sustainable travels (walking, cycling, using public transport rather than personal vehicles) reducing the volume of greenhouse gases, energy used, etc.

2.2 State of Developing Sustainable Urban Mobility Plans in Bulgaria

The overview of municipalities showed that by mid-2019, 11 Bulgarian cities are working on SUMP (Table 6). The plan status is at different stages of implementation. In Ruse, Burgas, Pleven and Gabrovo SUMP is in the process of implementation.

Table 6 Cities in Bulgaria working on SUMP, by 30.09.2019

No.	City	Population by 31.12.2018	Sustainable urban mobility plan status
1.	Sofia (capital)	1,241,675	The plan has been approved by the Municipal Council
2.	Varna	336,505	In the process of development
3.	Montana	39,240	The plan has been approved by the Municipal Council
4.	Veliko Tarnovo	68,859	The plan has been approved by the Municipal Council
5.	Kavarna	10,767	The plan has been approved by the Municipal Council
6.	Stara Zagora	135,715	The plan has been approved by the Municipal Council
7.	Kurdjali	43,263	The plan has been approved by the Municipal Council
8.	Ruse	142,902	The plan has been approved by the Municipal Council; in the process of implementation
9.	Burgas	202,434	The plan has been approved by the Municipal Council; in the process of implementation
10.	Pleven	96,610	The plan has been approved by the Municipal Council; in the process of implementation
11.	Gabrovo	52,169	The plan has been approved by the Municipal Council; in the process of implementation
12.	Montana	49,267	The plan has been approved by the Municipal Council

In the visions, defined in the plans, there is uniformity, related to striving for sustainable urban mobility, which is environmentally-friendly, safe and secure, accessible to the interest of people. At the same time, considerable differences are observed both concerning the horizon of planning and the goals. The similarities and the differences can best be seen between the sustainable urban mobility plan of Sofia and those of all the remaining cities. Let's take as an example the plans of Sofia and Ruse.

The plan for the capital is for the interval 2019–2035 and a vision for sustainable urban mobility. "Sofia is developing sustainable urban mobility which is protecting the environment and human health; oriented towards the people, not towards the automobiles, efficient and innovative; safe and secure; integrated and accessible to all. It contributes to transforming the capital into a green, attractive, smart, safe and accessible city".

Goals:

- reducing the negative impact of transport on people's health and on the environment (green city);
- increasing the attractiveness of the urban environment and ensuring better quality of life (attractive city);
- implementing transport innovations and strengthening the local mobility and economy (smart city);
- improving the safety and security of all stakeholders (safe city);
- integrated transport system, accessible for all (accessible city).

The distribution of travels on the territory of Sofia by 2017 is as follows: personal automobiles 30.7; walking 29.7%; urban public transport 37.4; bicycles 1.8; others 0.4.

The target indicators for travels as a percentage of the total number for 2035 is as follows: personal automobiles 23%; walking 28%; urban public transport 39; bicycles—10.

Concerning the environment for 2035, the following has been planned: total reduction of harmful emissions by 25%; the greenhouse gasses to decrease by 25%; noise pollution to be reduced by 10%.

The plan for Ruse has been developed for the period 2016–2026 with the following vision: "Achieving high degree of mobility in urban zones and suburbs in conditions of travelling with maximum accessibility, security, safety, and guaranteed environmental protection, to the interest of the local community and as foundation for stimulating internal integrity and sustainable development for the whole region".

Priority goals:

- increasing the efficiency and attractiveness of the public transport system;
- improving the quality of mobility and creating conditions for alternative types of travel;
- integrating the concept for sustainable mobility in the civic culture of Ruse.

According to the detailed study carried out in connection of developing a project Integrated urban transport system of Ruse, the distribution of travels on the territory of the city is as follows: walking—43.5%; automobile-driver—28%; public transport—20.1% (the ratio of bus rides and trolleybus rides is 59.4–40.6%, respectively); bicycles 2.4%; taxi 2.3%; automobile-passenger 2.1%; company transport (mini-bus) 1.1%; motorbike 0.5.

The share of travels by car (automobile-driver—28%, automobile-passenger 2.1%, taxi 2.3%) is 32.4% in total of all travels, which is almost 50% more than travelling with public transport.

The target indicators according to SUMP by 2026 are: increasing walking to approximately 50%, public transport usage to 24%, cycling to 2.5% and reducing travels by car to 21.5%. The remaining 2% are to be distributed among the other categories of the modal split.

3 Building a Sustainable Transport System in the Cities

3.1 Perspectives for Development of Transport Mobility in Cities

Solving the problems of the transport system of cities has been treated as a technical (engineering) challenge for a long time [7]. Some authors argue that solving the problems of sustainability of transport is hindered by the paradigm "based on vehicles", prevailing more than a century [8]. Technological innovations in transport (hybrid and electrical vehicles, biofuels, fuel cells, etc.) are usually viewed as an appropriate tool for ensuring a more efficient and sustainable transport system. Practice shows, however, so far concentrating on vehicle technologies has not led to the necessary transformations.

The transition of the current, unstable transport system to a low carbon mobility system in the cities requires profound structural changes both in terms of vehicle technology and in terms of mobility models [9]. The innovations in the field of mobility services have been linked to innovations in business models recently. One new characteristic of mobility services is that the business model is focused on a new type of value proposition, where users are looking not for product purchasing services (e.g. automobiles), but for sharing services (e.g. car sharing) [10].

Given the importance of innovation in car-sharing business models, two lines of business model literature can be identified. The first one describes business models as a reliable unit of analysis while the second describes them as a condition, essential for the commercialisation of new technologies [11]. For example, a few authors note that innovations in business models can unlock the economic potential of electric vehicles technology and support its adoption [12–14].

Based on review and analysis of both publications and good practices of mobility, we can define three potential paths, concerning the future of the mobility system in cities (Fig. 5):

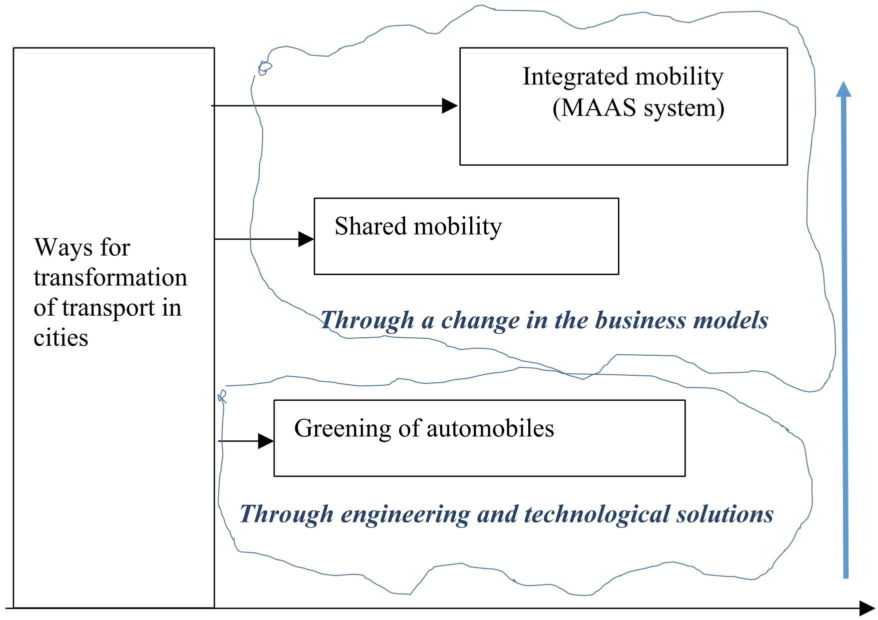


Fig. 5 Development of city transport system

- greening automobiles through engineering and technological solutions;
- shared mobility (carsharing, carpooling) through a change in business models;
- integrated mobility (Mobility as a Serves—MAAS) through a change in business models.

Each of the paths shown can be considered on its own, but their servicing (expanding the range of services and proposing complex solutions) along the shared and integrated mobility roads can create stimuli for ever faster technological renovation of the automobile fleet.

3.2 Greening of Automobiles Through Engineering and Technological Solutions

Key technologies are being developed worldwide such as using biofuels, electrical cars, hydrogen powered cars (using fuel cells), expected to contribute to reducing harmful emissions, including decarbonisation of transport. Biofuels are increasingly being explored as possible alternative to petrol and diesel. In this context, the following key documents have been adopted in Europe: Strategic Energy Technology Plan—“SET-Plan” [15], White Paper “Roadmap to achieving a Single European

Transport Area—towards a competitive, resource efficient transport system" by 2050 [16] and the package "Clean Energy for All Europeans", with a vision by 2030 [17]. In Bulgaria, the main relevant documents are: The National Development Program of Bulgaria 2020 [18] and the Integrated Transport Strategy for the period up to 2030 [19].

The perspectives for biofuels are reviewed in [20].

Hybrid, electrical and hydrogen vehicles have been developed and demonstrated at world exhibitions in recent years. The main car manufacturers are striving to be leaders in the future of green vehicles, using renewable energy sources [21–23].

3.2.1 Classification of Hybrid Vehicles

For decades electricity has been explored as an alternative energy source to replace or complement the internal combustion (IC) engines. According to [24] hybrid cars are divided into:

- Micro Hybrid—this is a car with a "Stop Start" system—the engine stops when the car stops (Volvo DRIVe, Volkswagen blue motion technologies);
- Mild Hybrid—this is a car upgraded with a "Stop Start" system, additionally upgraded with limited gain and regeneration to clean the catalyst (BMW active hybrid, Honda integrated motor assist) [25];
- Medium Hybrid—with additional upgrading over the microhybrid capacities with increased use of electricity, which allows reduction of IC engine power [26];
- Full Hybrid—it can operate for a while as electric car (Toyota and Lexus Hybrid Synergy Drive);
- Plug-in Hybrid Electric Vehicles (PHEV)—HEV. They can be recharged at the mains. Besides, they have a larger electric engine and battery, so they can operate as electromobiles for a significant period (Toyota Prius, General motors E-Flex system);
- Range Extended Electric Vehicle—this is predominantly electric car with a built-in generator for electricity production, which allows to increase the mileage of the car. For this purpose, an IC petrol engine is used. An example for this is Chevrolet Volt, which can travel for about 60 km on electricity, provided by a 16 kWh lithium-ion battery and electric engine of 111 kW. To ensure the additional mileage, a 1400 sm^3 petrol engine is used with 53 kW power. In this case, the mileage increases up to 500 km;
- Kinetic Hybrid Systems—they use additional devices to recover and reuse the energy obtained when the car stops, for example;
- Pure Electric Vehicles—these are not hybrid cars but they are included because they are expected to contribute considerably to the reduction of CO_2 emissions in the future and are beginning to be widely spread as alternative to IC engine cars (Tesla, Peugeot e-208).

The summarised features, shown in [24], of the different types of hybrid cars and electromobiles are presented in Table 7. The cars with the biggest number of

Table 7 Characteristic features of the hybrid cars

Functions	Micro hybrids	Mild hybrid	Medium hybrid	Full hybrid	Plug-in hybrid electric vehicles	Range extended electric vehicle	Kinetic hybrid systems	Pure electric vehicles
The IC engine stops when the car stops	x	x	x	x	x	x	x	
Stop-start of IC engine		x	x	x	x	x	x	
Charging when stopping		x	x	x	x	x	x	x
Low use of electricity to support IC engine		x	x	x	x	x	x	
Considerable use of electricity to support IC engine. Low power IC engines are used			x	x	x	x	x	
Short-term work as electromobiles, approx. около 3 km				x	x	x	x	x
Longer-term work as electromobiles, approx. 40 km					x	x		x
Long-term work as electromobiles, approx. 160 km								x
Use mainly rechargeable batteries that are charged at the mains (electromobiles)					x	x		x

functions are the Plug-in Hybrid Electric Vehicles and the Range Extended Electric Vehicles.

The all-electric vehicles use electric engines, charged by rechargeable batteries rather than IC engine. In this way the CO_2 are considerably reduced. It is assumed that the emissions from the car are zero, but since electricity from the mains is used for the production of the electromobiles and for charging their batteries, the value of the CO_2 depends directly on the emissions from the electricity production. In countries like Norway and Iceland, the electricity is mainly generated by renewable energy sources [24] and we can assume that the CO_2 emissions are relatively small—under 50 g/100 km. In the remaining countries, including Bulgaria, these quantities are over 50 g/100 km and reach up to 100–130 g/100 km. For these cars, the distance travelled with a single charge is short—about 50–60 km for the most widely used cars, and up to 300–450 km for the newest models like Tesla, Peugeot, etc. Besides, the battery life is limited.

A better option of the electric and hybrid car is the one that can be charged from the mains at night or at downtime, outside peak load of the mains. Another appropriate option is for charging to be done by power stations, generating electricity from renewable energy sources such as wind, sun, water or biomass.

Many governments all over the world allocate grants (Germany, Japan, the USA), to support the development of technologies and the implementation of these cars into people's lives through subsidizing their use.

3.2.2 Technological Solutions for Using Electricity in Bus Passenger Transport

In public passenger transport, besides trains on the subway, trams and trolleybuses, which are powered by electricity, tests and trials are aiming at the deployment of buses powered only by electricity or by hybrid drive. The scheme that is available in the hybrid drive to extend the range of electricity offered by Volvo is presented in Fig. 6 [27].

Driving on flat terrain and downhill is to be carried out only by electric drive and ascending on sloped terrains is to be executed by hybrid or internal combustion drive. Moreover, according to the length of the route, charging stations are also planned to be easily accessible. The Volvo 7900 Electric bus is 12 m long, 2.55 m wide, 3.28 m high for 83 passengers, 35 of which are seated with the driver. The drive is executed by a 160 kW electric motor, with a torque of 400 Nm, using lithium-ion 4 × 19 kWh batteries or a total of 76 kWh, the gearbox has two gears. Charging is fully automated, with the charger on the roof of the bus and takes only 6 min. The current is in the range of 200–400 A at a voltage of 500–750 V. The bus has two axles and is available in electric and hybrid versions. A hybrid variant is used in Stockholm, Sweden in an 8 km long route.

In 2015, the "Strategy for Development of Sustainable Transport System in the Calarasi—Silistra Cross—border Area" was established under Clean Access Project in the Calarasi—Silistra cross—border area/Clean Access in Calarasi—Silistra Cross—Border Area "—Cleea/Ref. No 2 (3 i)—1.1-7 MIS—ETC CODE: 118",

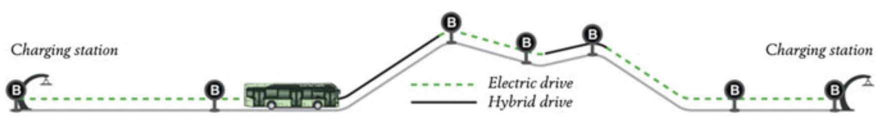


Fig. 6 Scheme for using hybrid buses on different routes

financed under the Romania—Bulgaria Cross Border Cooperation Program 2007–2013 with a leading partner The Institute of Electrical Engineering/INCDIE ICPE—CA/Bucharest, and partners Angel Kanchev University of Ruse, National Institute for Research and Development of Gas Turbines in Romania, municipality of Silistra and municipality of Calarasi [28]. It presents test results of the BYD bus K9 of the Chinese company BYD Company Ltd, powered by electricity. In 2013, in Timisoara, Romania, a bus has been tested with a 200 km run on a single charge. The bus has the following characteristics: autonomy of 250 km with one charge in urban traffic; dimensions (L/B/H): 12 m/2.55 m/3.36 m; seats: up to 72 passengers (31 seats), with a maximum authorized mass of 18,000 kg; cost per 100 km approximately 130 kWh, acceleration: 0–50 km/h in 20 s; maximum speed: 70 km/h; charging: full charging 6 h, fast charging 3 h: battery capacity: 324 kWh/600 Ah with battery life expectancy of about 4000 charges; standard charging duration 5 h—60 kW, 480 V, alternating three-phase current.

Another variant of a proposed electric bus for which technical data from testing and operation is known is the YTP-1 model, produced by the Dutch company Ebusco, Fig. 7.

In 2015, the bus was tested between Munich and Berlin on a 450 km route. A new type of battery with a capacity of 3000 charging cycles was used and a power rating of 1:3.5 kWh/kg. In 2013, the Dutch Organization for Applied Scientific Research (TNO) researched and published a report (TNO 2013, R10212) on test results of this type of bus on battery autonomy using the SORT (Standardized On-Road Cycles) procedure.

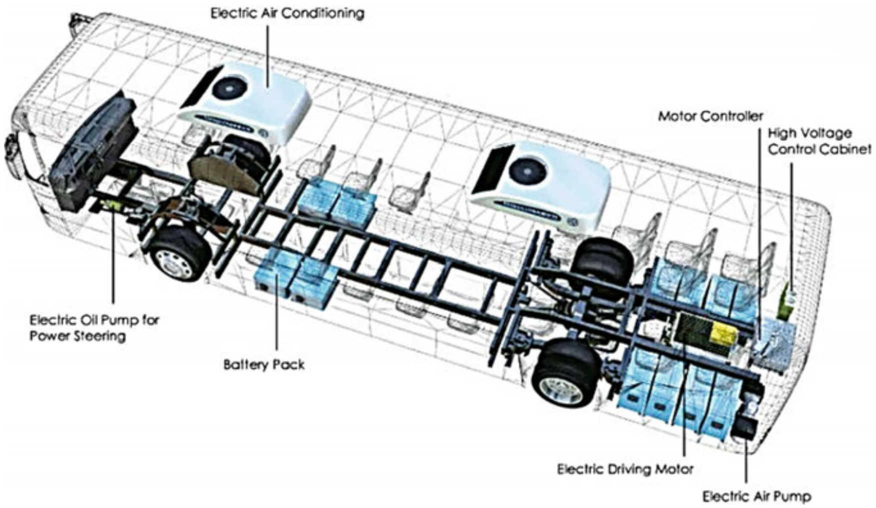
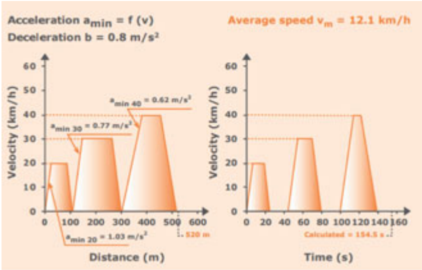
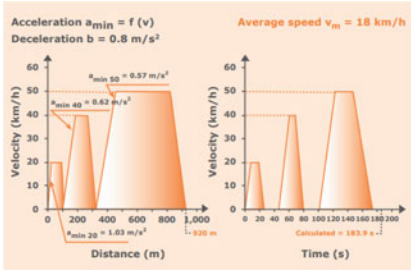


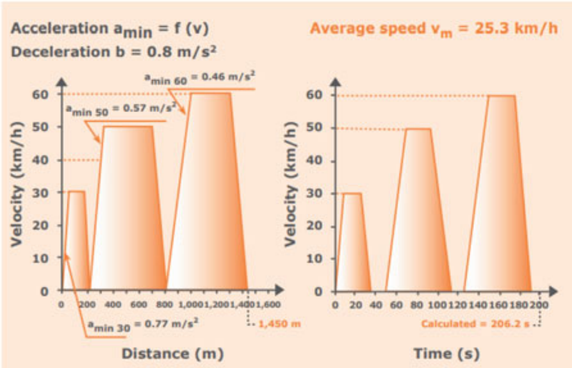
Fig. 7 General view of the Ebusco electric bus model YTP-1



(a) Heavy urban traffic



(b) Easy Urban



(c) Easy Suburban

Fig. 8 Test cycles for electric buses [29]

According to the procedure, the tests were carried out over a period of three test cycles: SORT 1: busy urban route; SORT 2: low-loaded urban route with moderate traffic flow; SORT 3: easy surrounding route, Fig. 8 [29].

The battery of the bus had a mass of 2400 kg and provided a range of up to 250 km. The total mass of the bus with a load was 14,410 kg. In the tests, the following data were obtained: for SORT 1: busy urban route: where for a mileage of 5395 km was spent 6.21 kWh, which is 115 kWh/100 km; SORT 2: a slightly busy urban route with a moderate traffic flow at 8386 km where 9.57 kWh was used, which is 114 kWh/100 km; SORT 3: an easy roundabout route for a mileage of 11,181 km, using 12.87 kWh, which is 115 kWh/100 km. For a distance of 177 km covered in 7.5 h, an average of 210.85 kWh was charged, which is an average of 119 kWh/100 km.

Electrical buses can be tested through the suggested SORT procedure to determine energy consumption per 100 km, similarly to the procedure for determining fuel consumption for IC engine driven buses.

3.2.3 Technological Solutions for Using Hydrogen Fuel Cell in Passenger Transport

Hydrogen is considered to be energy without CO_2, if it is produced by renewable and nuclear energy. Hydrogen fuel cells can increase the efficiency of energy consumption. The problem is that with the current technologies, the processes for the production, storage, transport and distribution of hydrogen, as well as the hydrogen fuel cells themselves are very expensive and reflect on the price of the fuel cell powered vehicle, making it still rather high. In terms of emissions, if hydrogen comes from renewable energy sources, it is assumed that the vehicle produces zero CO_2 emissions.

The advantages of hydrogen powered vehicles, compared to electrical and hybrid ones, can be defined in several aspects:

- charging time is considerably less (3–10 min, compared to the best time of 40 min, or the most common 3–6 h with the electrical vehicles);
- hydrogen powered vehicles can travel 2–3 times longer distance with one charge;
- hydrogen powered vehicles solve the problems, that the electrical vehicles have in relation to the battery lifetime;
- hydrogen can be stored for a long time, unlike electricity;
- hydrogen powered vehicles are seen as opportunities for the circular economy;
- hydrogen powered vehicles have low level of noise and good acceleration (the hydrogen car is powered by electrical engine, with energy coming from the oxidation of hydrogen. This immediately results in two main advantages—low noise level and reaching maximum torque almost immediately, which means very good acceleration).

In recent decades a big part of the resources for research and development have been involved in the hydrogen and fuel cell technologies. They attract significant interest from the politicians and private investors.

Hundreds of demonstration projects are being implemented globally, expecting commercialization. The main challenge is to reduce the costs of these technologies.

Hydrogen fuel cells are considered better in the long run, provided the costs can be reduced to an affordable level.

Currently, there exist a number of vehicles, driven by hydrogen fuel.

Automobiles

Together with the electrical vehicles with rechargeable batteries, cars driven by hydrogen fuel cells are the only alternative for zero emission propulsion for motorized private transport. The first fuel cell cars were tested in the 1960s as demonstration projects. A new impetus for the development of fuel cells came in the 1990s. In most cases, the vehicles for testing fuel cells were transformed automobiles which initially had IC engines. At that time, however, the early test models were still not competitive technically or economically. In addition, up to 10 years ago, the prototypes of petrol engines were still tested with hydrogen as an alternative energy and fuel with low emissions.

Now there exists extensive hands-on experience with fuel cell prototype cars [21, 30]. A number of large car manufacturers have started to offer early production cars, which are now as good as the conventional cars with IC engines in terms of functionality. The number of fuel cell vehicles is projected to grow from several hundred to several thousand in the coming years. The average price for a fuel cell car is still much higher than that for ICE powered vehicles, reaching around 60,000 EUR.

The fuel cells in the latest car models have power of 100 kW or more. In comparison with the battery electrical cars, they have a wider range of about 400–500 km, with a lower vehicle weight and much shorter charging periods—from 3 to 5 min. Usually, they carry on board 4–7 kg compressed hydrogen for generating electric energy in a fuel cell, to power the vehicles. This hydrogen is stored in tanks under pressure of 350–700 bar [31].

According to research [21], a car of medium class such as Honda FCX Clarity, with 100 kW electric engine can travel about 460 km with one tank of hydrogen under pressure of 350 bar. Other cars, using hydrogen fuel cell, which have a high mileage with a single charge are: Toyota FCHV-adv, hybrid version with estimated mileage of 830 km; Mercedes-Benz B-Class F-Cell with estimated mileage of about 400 km; Nissan X-TRAIL FCV with estimated mileage of 480 km; GM HydroGen4 travels 320 km with a single charge of 4.2 kg hydrogen, and average consumption of 1.31 kg/100 km.

The use of hydrogen as fuel is presented in Toyota Mirai, in Fig. 9 [32]. The system consists of two hydrogen tanks, type 4, holding 5–8 kg hydrogen under pressure of 700 bar, with a capacity of 122.4 l (front tank: 60.0 l; back tank: 62.4 l).

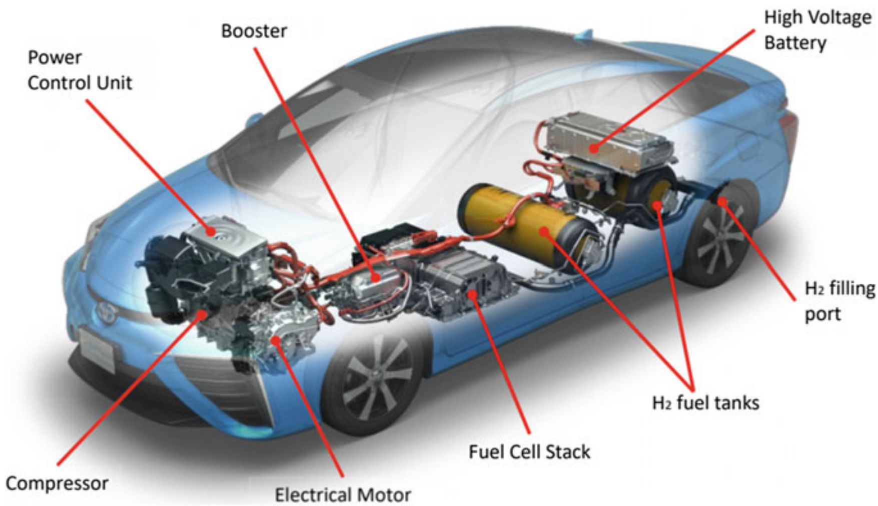


Fig. 9 Scheme of electrically powered hydrogen driven Toyota car

When testing a Toyota Mirai FC Stack with a weight of 1850 kg, maximum power of electric engine 113 kW (154 к.с.), maximum torque 335 Nm by JC08 factory test cycle tourism, the mileage determined was around 480 km with a single charge.

Another car manufacturer is Mercedes. The hybrid car, driven by electricity and hydrogen is Mercedes-Benz GLC F-CELL. It is characterised by: electric battery for a mileage of up to 51 km NEDC with capacity 13.5 kWh (9.3 kWh usable); hydrogen tank with capacity 4.4 kg under pressure of 700 bar; mileage on hydrogen 478 km NEDC; hydrogen consumption about 0.92 kg/100 km; electric engine power 155 kW and torque 365 Nm; maximum speed 160 km/h (100 mph). With combined power supply, electricity consumption is 13.7 kWh/100 km.

Buses

Buses in the public transport network are the most tested area of application for hydrogen and fuel cells. Since the beginning of the 1990s, several hundred busses have been operated worldwide—mostly in North America, Europe and more and more in Asia.

Although initially the hydrogen is still used in busses with IC engines, the bus developers are concentrating almost completely on electric buses with fuel cells (FCEB). Using small transport fleets of FCEB is encouraged in urban areas as a way of contributing to technological development and clean air policy.

Fuel cell buses have reached a high level of technical maturity although they are not in serial production. That is why, due to their small number, they are still quite expensive, around 1 million Euro, compared to standard ICE buses, which cost around 250,000 Euro. Maintenance cost are significantly reduced and reliable operating times are increasing [33].

Depending on the annual numbers produced, the production costs for FCEB are expected to decrease. It is estimated production costs for 12 m buses to reach up to about 450,000 EUR by 2020 (purchasing 100 buses) and up to about 350,000 EUR by 2030, which makes them competitive.

Often contemporary fuel cell buses use energy from two groups of fuel cells, each with approximately 100 kW power. They have a relatively small traction battery and they can recover energy when they stop. Their tanks hold from 30 to 50 kg compressed hydrogen under pressure of 350–700 bar. This allows them to travel from 300 to 450 km by one charge and that is why they offer almost the same flexibility as diesel buses on a daily basis. The older buses have a higher consumption of over 20 kg hydrogen per 100 km, but the ever more modern fuel cell buses use about 9 kg per 100 km. This provides an advantage for FCEB in terms of energy efficiency of about 40% compared to diesel buses, which have a consumption of about 30–40 l diesel fuel per 100 km. In relation to this, it is expected the automobile fleet of FCEB in Europe to grow and surpass 300–400 vehicles by 2020.

The technology for obtaining electricity from hydrogen fuel cells in buses is studied in [34]. In Fig. 10, the layout of the Van Hool bus, which is used for passenger transport in Aberdeen, Oslo, Cologne and London is presented. The bus used in Oslo has the following characteristics: fuel cell system with 150 kW; batteries 100 Ah;

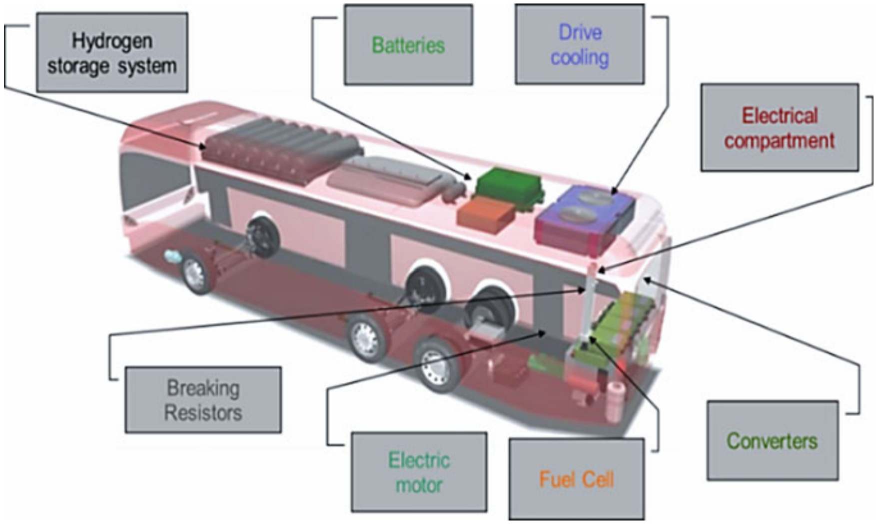


Fig. 10 Hydrogen fuel cell bus Van Hool

a hydrogen storage system including 7 tanks with air pressure of 350 bar; full tank capacity 35 kg.

The bus has 3 axes, the fuel cells are in the back and the hydrogen tanks are on the roof. The drive is on the last axis in the back.

The scheme of EvoBus is analogous. Its specifications are as follows: the bus has 2 axes, the back one is with the drive; the fuel cell system is 120 kW; batteries 250 Ah; the hydrogen storage system includes 7 tanks with 350 bar pressure; full capacity of tanks 35 kg.

Under the project "Clean hydrogen in European cities" (CHIC) 54 electric buses with hydrogen fuel cells of the manufacturers APTS, EvoBus Mercedes-Benz, New Flyer, Van Hool and Wrightbus [34] have been tested for the period 2010–2016. The tests were conducted in: Aapray, Switzerland 5 buses, Bolcano, Italy—5 buses, London, Great Britain—8 buses, Milan, Italy—3 buses, Cologne and Hamburg, Germany 4 buses each, and Oslo, Norway—5. In addition, 20 buses were tested in Whistler, California. The test results showed that for a daily urban mileage under 350 km, similar to that of a diesel engine bus, with charging at specialised stations for hydrogen for under 10 min, the average consumption for a 12 m bus is 9 kg hydrogen/100 km. This is equivalent to 30 l diesel fuel per 100 km.

Based on this research it can be assumed that 7 bottles of hydrogen with total volume of 35 kg would be sufficient for covering the average daily mileage in urban and suburban conditions for a 12 m long bus.

Trolley Buses, Trams

Trolley buses with fuel cells and a set of batteries, which allow them to travel autonomously for up to 100 km without energy, provided by overhead wires, have been put in operation in Riga, Latvia. The idea is to make trolley buses independent from the mains as much as possible, so they can travel freely like buses in areas without overhead wires.

A tram, holding 380 passengers, driven by hydrogen fuel cell, has been developed in China. With one three-minute hydrogen charge, the tram can travel 100 km at average speed of 70 km/h. The average bus route length is 15 km. This allows the tram to make three turns on the route with one charge.

Railway Vehicles

In electric-driven locomotives the power is supplied via fixed current wires (overhead lines, wires) and current collectors on the vehicles. For technical, economic or other reasons, however, not every railway line can be electrified. The large initial investment, needed for electrification of the lines, can't always be justified, especially along lines with a small passenger flow.

Railway vehicles, using hydrogen as energy supply and energy source, can serve as additional alternative. Railway vehicles with fuel cells combine the advantage of operation without pollutants and that of low infrastructure costs, compared to those for operation with diesel fuel.

Air Transport Vehicles

In civil aviation, hydrogen fuel cells are considered potential energy suppliers for the air transport vehicles. They can supply electricity to the electric system of the aircraft as emergency systems or auxiliary power supply unit. The more advanced concepts include starting the main engine at the airport by commercial aircraft.

Water Transport Vehicles

In both aviation and navigation, fuel cells are tested as complementary systems with energy, needed for onboard power supply. Using hydrogen fuel cells for ship propulsion is still at an early stage of designing or testing. It is implemented only in smaller passenger vehicles, ferry boats or entertainment vessels [28, 35]. So far, however, fuel cells have not been used on large commercial ships.

3.2.4 Other Technological Solutions for Using Electricity and Hydrogen Fuel Cells for Vehicles

High school and university student teams from Bulgaria are working on issues of energy efficiency and developing prototypes of electrical cars for participation in the world competition Shell Eco-marathon. In 2019 at the competition in London three Bulgarian teams took part:

- a student team from the University of Ruse;
- a high school student team from the Professional High School of Agriculture, Forestry and Tourism "N. Y. Vaptsarov", Chepelare;
- a high school team from the Professional High School of Mechanical Engineering and Electronics in Burgas.

Automobile of the Professional High School of agriculture, forestry and tourism „N. Y. Vaptsarov", Chepelare

Automobile of team "Motorist" of the University of Ruse "Angel Kanchev"

Automobile of Professional High School of Mechanical Engineering and Electronics in Burgas

Fig. 11 Prototypes of the electric cars of the three Bulgarian teams, participating in Shell Eco-marathon in 2019 in London

In Fig. 11, the prototypes of electric cars that the participating teams developed are shown.

The Professional High School of Agriculture, Forestry and Tourism "N. Y. Vaptsarov", Chepelare started its participation in Shell Eco-marathon Europe in 2013. They have competed in the category "prototypes, powered by an electric battery". The team develops a new design and improves their car every year. In 2019, the high school team reached a position among the Top 5 in the competition in their category.

The University of Ruse has participated in the same category with an automobile, developed by lecturers and students from the Club "Motorist". Through the years, the team proved the quality of its work, making it in the Top 10 in their category.

In the period 2009–2014, Technical University—Varna participated in Shell Eco-marathon Europe. Back in 2010 they achieved the remarkable third place in the category "prototypes, powered by propane-butane". In 2014, the team participated in the competition for the first time with an automobile in the category "urban type". In the last four years, the university does not participate in the competition.

In 2019, student teams from the University of Ruse and the Technical University, Sofia participated with prototypes of urban cars powered by hydrogen (Fig. 12). Both prototypes are the first demonstration projects of Bulgaria in the field of hydrogen mobility. The academic responsibility of the Rector's bodies of the two higher

Prototype of TU Sofia Prototype of the University of Ruse

Fig. 12 Prototypes of electrical automobiles, powered by hydrogen fuel cell, developed by the two Bulgarian teams that participated in Shell Eco-marathon in London in 2019

schools, referring to the beginning of the development of hydrogen mobility in the country is notable.

It should be noted that the Technical University—Sofia is the first Bulgarian participant in Shell Eco-marathon Europe. Since 2008, the team has competed in the category "Urban type". In the beginning, the students developed hybrid engines. Then they started working on electric engines, using electric battery (plug-in) or hydrogen fuel cell in the different editions of the competition. In 2019, they participated in the competition with an automobile powered by hydrogen fuel cell.

In 2017, the University of Ruse added a new team in the competition—"HydRU Racing Team", which competes in the category "Urban type", powered by hydrogen fuel cell. Through the years, the team has developed three completely new concepts of the automobile. In 2018, on the London racing track, the team won the worthy fifth position with the automobile HydRU R3.

The road to engineering and technological solutions for decarbonisation of transport is the traditional one—tried and tested, but it has not yielded the expected results for building a sustainable transport system yet. The technological road with a focus on green cars is not sufficient. A change in transport practices and behaviour is needed [36]. This change can be successful with new business models such as carsharing and using a transport service after giving up your personal car.

3.3 Comobility

Comobility or Carsharing (Fig. 13) and Carpooling (Fig. 14) is a possible option for the future of the transport system. It continues the trend for green cars, but adds a business model to carsharing.

The economy of sharing has been recognised as a global phenomenon, which allows people to share opportunities and markets by using new tools. The term "economy of sharing" refers to a market situation, in which people share products and the use of different services. Unlike the ownership of all the necessary equipment (such as vehicles, homes or goods), the economy of sharing is attracting more and

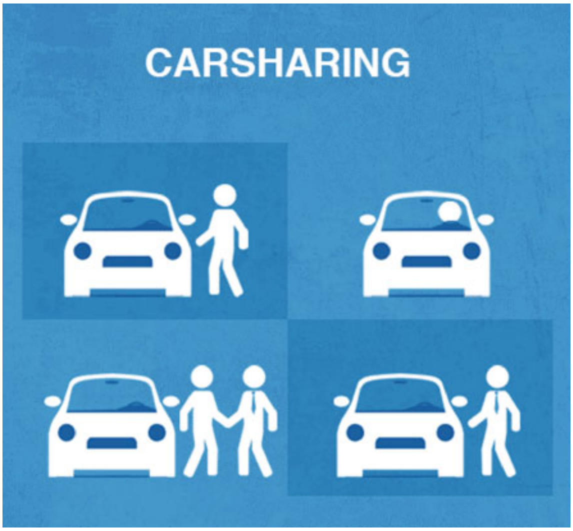


Fig. 13 Comobility—carsharing

Fig. 14 Shared mobility "carpooling"

more interest since people want more and more to reduce costs for maintenance, storage, insurance, etc. Concerning mobility in the cities, the economy of sharing has emerged as sharing cars, bicycles, drones and other individual means of transport.

Carsharing has as primary goal reaching a given destination, often at a lower individual and social price, compared to using your own personal vehicle. As a result, household purchasing power is increasing since they do not need to by or maintain an automobile or other individual transport vehicle.

The Swiss Academy of Mobility, which organised this year's conference on the issues of carsharing, called Wocomoco [37] (WOrld COllaborative MObility COngress), defines carsharing or cooperative mobility in the following way:

> Comobility focuses on sharing trips, transport vehicles and infrastructure. At the borderline between public and private transport new networks, based on equal partnership, encouraging new modes of individual mobility, different from personal car ownership.

Under "comobility" we understand sharing cars, bicycles, drones and other similar individual means of transport. The platforms for reserving taxis or shared trips by car are also elements in this category. The conventional public transport is not part of this model and neither are the traditional services for car hiring, where you book the vehicle and not the mobile service it provides.

The systems for comobility require at least one smart component: the mediation platform. Besides, using information and communication technologies for developing smart transport systems (STS) and cooperative smart transport systems can mace comobility even smarter.

Comobility can make people prefer cycling, public transport, shared trips or a combination of these modes of travelling to driving a car. One automobile fleet for shared use would more probably include vehicles powered by electricity, natural gas or hydrogen than a private automobile fleet.

Mobility services such as automobile and shared trip are increasingly seen as a means of changing to a more sustainable transport system and are related to a better city management; improvements in the energy efficiency and the quality of air in the city; increased usage of renewable energy sources; reduced congestions and improved accessibility [38–41].

Although stimulated by the new mobile technologies and applications, carsharing is first and foremost a non-technological innovation, focused on the changes in the travelling behaviour as a practice [42, 43].

"Carsharing" refers to using one or more shared automobiles by more drivers, Fig. 13. Carsharing is often used as a synonym to the term "shared car". Practically speaking, sharing cars in the city functions as a short-term hiring of a car by self-service, i.e. there is no personnel on the spot, when a car is taken or returned.

In combination with public transport, cycling, etc., it creates a service. This is a concept, which meets the requirements for competitive mobility, alternative to using personal cars, especially in built-up areas. Carsharing started to be offered as a service and to be more widely used in bigger cities. It is especially popular in Switzerland, Austria and Germany, but it is also gaining more and more popularity in countries like the Netherlands, Belgium, the USA, the UK, France, Canada and Spain.

There are many reasons why people are thinking about and developing the concept for carsharing.

Within cities, it is mostly carsharing that helps to achieve not only the priority goal "reducing liquid fuel consumption", but also the goal "improving the environment through increasing the use of public transport, cycling and walking, rather than using personal automobiles".

Carsharing also contributes to reducing costs in the cities. Shared mobility contributes to:

- fewer car trips, less air-pollution;
- stimulating and increasing the use of public transport and cycling;
- reducing costs in the city;
- more efficient use of urban space;
- more efficient use of parking lots;
- increased accessibility and better economy;
- increased traffic safety, etc.

Fewer car trips, less air-pollution. International research shows that the number of car trips is reduced by 20–30% or more when the car owner joins the service of carsharing. The personal car trips are largely replaced by public transport, walking or cycling. On the other hand, there are no data, for a significant increase of car trips by people, who have not owned a car before and who join carsharing. Instead, carsharing replaces the car hire and borrowing cars from friends.

Those who are familiar with carsharing usually drive newer cars than those of people, using their own cars. This reduces the emission of exhaust gases, which, additionally contributes to reducing the impact on the environment.

The number of short trips is drastically reduced when former car owners join the carsharing service. This is due to the fact that users of automobiles have to plan better, thus reducing considerably the real costs of travelling.

The harmful emissions quantities are the highest for short-distance trips. That is why reducing these trips is of particular importance for improving the air quality in cities.

Stimulating and increasing the use of public transport and cycling. Users of carsharing use public transport and cycling for their daily routine trips, and the automobile is more of an additional means of transport. Research clearly shows that users of carsharing increase the use of public transport and this increases the revenues of the latter.

Reducing costs in the city. Cars for sharing are usually used more than the personal car since more people are using them. In addition, the need for booking means better planned and thus more efficient trip. As a result, costs are lower while demand for automobiles generally and for parking places is reduced.

More efficient use of urban space. Reducing the number of automobiles in the city, due to reducing the use of personal cars in favour of shared ones leads to streets that are not so busy and creates better conditions for efficient use of urban space.

More efficient use of parking lots. In reference sources it is noted that one shared car replaces 3–5 individually used ones because it is used more efficiently (Some authors claim that one shared car replaces up to 10 individually used ones). Consequently, shared automobiles can free valuable space in the cities as they replace a large number of private cars, which are used by one or two users only. Thus, the limited parking space in the city is used more efficiently by more people. In other words, carsharing can help to reduce the search for new parking places, the waiting time for a parking place or the time for looking for a free place to park, as well as the number of vehicles that are looking for existing parking lots.

Increased accessibility and better economy. Carsharing contributes to better accessibility for urban residents, especially for people who are not motivated or cannot afford to own a car, but still need to use one occasionally. For many of the city residents, who do not need a car on a daily basis, carsharing offers substantial savings, without reducing accessibility.

Increased traffic safety. Carsharing increases traffic safety due to the reduced number of automobiles and also due to the fact that as a rule, the cars used in this mode are generally newer than the average private car. Shared cars have better safety features and collision protection. Besides, they can be equipped with additional smart systems, aiding the driver for a safer work environment [44].

Carpooling is sharing trips with more people travelling in one car (Fig. 14). Thus, travelling by car reduces the travel costs for each person.

A number of authors view innovations in business models as decisive for the commercialization of new technologies [45–47]. In some studies, it is noted that business models based on sharing a car can unlock the economic potential of the electric vehicle and support its recognition [12–14, 48]. Innovations in business models are also connected to vehicles with hydrogen fuel cells and recycling of materials, similarly to the principle of circular economy.

At present, most companies for carsharing like Uber, Zipcar and Car2Go have chosen the densely populated urban areas because of the commercial opportunities. The cities are where the work places and residential areas are concentrated and have the best accessibility to public transport. The possibility for integrating different kinds of transport is also biggest in such areas. Carsharing is an applicable alternative in the suburban areas as well since it ensures the mobility of residents.

Despite the advantages of carpooling, the initiatives and schemes are still rather fragmented, the transport companies still compete with the private cars, instead of cooperating, thus still being unsuccessful in creating conditions for transforming of the existing mode of travel in the cities.

3.4 Integrated Mobility

Talking about the future of the transport system, we should note the transformation of mobility into "integrated mobility" MaaS (Mobility as a Service). This can be traced in the intermodal mobility services [49, 50].

The most frequently cited definition for mobility as a service (MaaS) comes from MaaS Alliance (a non-governmental organisation, founded on the basis of public-private partnership, https://maas-alliance.eu/the-alliance/), which defines the concept as "integrating different forms of transport services in a unified mobile service, accessible on request". According to this definition, MaaS can take into consideration a number of modes and include a variety of functions, for example, unified mobile application, multimodal trip planning, service packages, fixed monthly subscription or direct payment. A unifying feature if each MaaS implementation is the integration of many services.

Three levels of integration in MaaS can be defined:

- *level 0*—no integration: only single services;
- *level 1*—integrating of information: planning of multimodal trips, information about prices of trips;
- *level 2*—integrating of the booking and payment: single trip—find, book and pay;
- *level 3*—integrating of the services offered: packages/subscription, contracts, etc.;
- integrating of public goals: policies, stimuli, etc.

Mobility as a service (MaaS) is the integrating of different modes of transport services into a unified mobile service, accessible on request. To answer to a client's order, MaaS operator facilitates the variety of modes of transport, no matter whether they are public transport, carsharing, cycling, taxi, car hired/leased, or a combination of them all. For the MaaS user an added value can be offered by using an app for providing access to mobility, with one channel of payment, instead of a number of tickets and payment transaction.

The successful MaaS service also offers new business models for organising and implementing various transport options, with some advantages for transport operators, including access to improved user information and looking for new options for serving unsatisfied searches. The aim of MaaS is to present an alternative for using the personal automobile, which can be as convenient, more sustainable, helpful in reducing congestions and limitations in transport capacity, being cheaper all the way.

Instead of selecting, booking and paying the trips with every type of transport separately, users are allowed by the digital platforms offering MaaS to organise their travels "door-to-door" by using a single app. In this way, the MaaS concept provides new generation transport services, which are user-oriented. It gives answers to questions such as: How to transport the passengers to their destination, taking into consideration the travel conditions and the state of the transport network in real time, by evaluating all possible options and considering the personal preferences of each user (e.g. time and convenience, compared to the cost of travel) and offering instant mobile payment for the services.

The main advantages of the MaaS system are the following:

- improved quality and convenience of travelling (i.e. personalized and hassle-free travelling on request);
- ability to help passengers select the most efficient means of transport, taking into consideration travel costs as well;
- improved transport networks;
- detailed monitoring, management and planning of mobility services;
- fewer congestions and environmental problems ensuing from transport;
- reduced mobility costs due to the availability of a wider range and larger number of providers;
- increase of revenues for the transport service providers;

- enhanced regional reaction to the emergence of new transport services.

The main characteristics of MaaS are presented in Table 8 [51–54].

In Table 9 are shown pilot MAAS projects. UbiGo is a small pilot project in Goeteborg, Sweden, which was expanded at the end of 2016 to other cities in the country; MaaS in Helsinki. Finland (Whim app) is a pilot project, starting in 2015, which transports a private start-up into MaaS Global. In Germany, the Deutsche Bahn offers Qixxit as a national system, which offers planning of travels with public and private transport and allows one-time payment for all vehicles used within one trip.

The private platform Bridj is an example of offering such services in three cities in the USA—Boston, Kansas City, Washington. The services are limited to trips between residential areas and business zones. The minibus routes are dynamic, according to the points of getting on and off and in this way trying to ensure a correspondence between demand and supply of transporting vehicles. The price for these vehicles is slightly higher than the price for public transport, but significantly lower than the price of taxi service. The platform Beeline SG in Singapore is pilot and is part of the national smart initiative. In terms of functionality and opportunities it is between Whim app and Bridj. SMILE is a project developed by a big team, consisting of experts in different spheres. It starts in 2012 and approximately 140 people turned the idea into a working prototype. The project was initiated by Wiener Stadtwerke and financed by the energy and climate fund of the Austrian federal government and is part of the third call of the programme "Austrian leading projects for electrical mobility". All functions of the mobility platform were tested for more than a year. Then the changes in mobility behaviour were studied. More than 1000 external users were registered for the pilot operation and tested the platform and its functions elaborately. After that, all users of the test filled in an online questionnaire to evaluate their experience. 75% state that they were very satisfied or satisfied and suggest improvements of the application. The research team of the technical university in Vienna checked whether the use of the platform led to a more eco-friendly behaviour of mobility. The results showed that almost half of the respondents (48%) stated that they started using public transport more often, 21% reduced the use of their own automobiles. The platform also stimulated intermodality because 26% of the respondents stated that they combine car and public transport more often and 26% combine bicycle with public transport more often. The platform Communauto was developed in Quebec and combines public transport, taxis, shared automobiles and bicycles.

3.5 Servitising of Urban Transport

It is important to know that the three directions (through engineering and technological solutions, shared mobility and integrated mobility) given for the future of transport in cities are not separate. Servitising (expanding the scope of services and suggesting complex solutions) of transport along the shared and integrated mobility

Table 8 Main characteristics of MaaS

Main characteristic	Description
Integrating of modes of transport	The aim of MaaS is to encourage the use of public transport services by uniting multimodal transport and allowing the users to select and be facilitated in their multimodal travelling. The following modes of transport can be included: public transport, taxi, car sharing, bicycle sharing, car hire, bus services on request. An option "select the most environmentally-friendly mode of transport" may be included in the platform. Presenting the service outside the city limits will include long distance buses and trains, airplanes and ferryboats
Tariff option	The MaaS platform offers to the users two types of tariffs for using mobile services: "mobility package" and "pay when you travel". Packages of different modes of transport, including a fixed quantity of trips km/minutes/destinations to be used by paying a monthly fee are presented. The second type of tariff, "pay when you travel", charges users according to the effective use of the service
One platform	MaaS relies on a digital platform (mobile app or web page), through which end users have access to all services necessary for their travels: planning of travel, booking, selling tickets, payment and information in real time. Users can have access to other useful services as well, for example weather forecast, synchronising with a personal activity calendar, report on travels, invoicing and feedback
Numerous participants	The MaaS eco-system is built on interactions between different groups of participants through a digital platform: looking for mobility (e.g. an individual or business client), supplier of transport services (e.g. public or private) and platform owners (e.g. a third party). Other participants can also cooperate in order to ensure the functioning of the service and improve its efficiency
Technology use	Different technologies are combined: devices, e.g. portable computers and smart phones; reliable mobile internet network (WiFi, 3G, 4G, LTE); GPS; electronic tickets and a system for management of database and integrated infrastructure by technologies (i.e. IoT)
Registration requirements	The end user is required to join the platform for access to the available services by registering. The profile can be valid for one person or, in some cases, for the whole household. Subscription not only facilitates the use of services, but also allows personalising of the said service
Personalisation	Personalisation guarantees that the requirements and the expectations of the end-users are met more efficiently, taking into consideration the uniqueness of each client. The system provides the end user with specific recommendations and individual solutions based on his/her profile, preferences expressed and previous behaviour (e.g. history of travels). Besides, they can connect their social network profiles through their personal MaaS account

Table 9 Pilot MAAS projects, implemented worldwide

Applications	Company	Country
Whim app	MaaS Global	Finland
UbiGo	Go: Smart by Lindholmen Science Park; Vinnova	Sweden
Qixxit	Deutsche Bahn	Germany
Beeline	Infocomm Development Authority; Land Transport Authority	Singapore
SMILE	Wiener Stadtwerke; Wiener Linien; Austrian Federal Railways	Vienna, Austria
Bridj	Bridj Inc	Boston, Kansas City, Washington, USA
Communauto	Communauto	Quebec, Canada

routes can create stimuli for an ever-faster technological upgrading of automobile fleets.

Furthermore, servitising of products has been created, in analogy to circular economy [55]. The services for intermodal mobility show that the promotion of more sustainable modes of transport such as cycling and walking is encouraged [56, 57].

In addition, the integration of telecommunications, energy services and transport through intermodal mobility services in a mid-term and long-term perspective are seen as a considerable capacity for innovations [58–60].

Managing the transition to integrated mobility is not easy—it is not entirely clear how shared and integrated mobility pathways are to be categorised. On one hand, they can be seen as purposeful transitions into this state and the participants actively support activities, which can lead to transformation [61]. The integrated pathway, however, can better be described with the help of the transition to intermodal mobility, where the systems are focused on the alignment of business models and positions of the participants while every new participant has an impact on the organisation of the MaaS system [62, 63].

4 Prospects for Alternative Water Transport

Ten Bulgarian cities are located on the river Danube. Using water transport as an alternative to urban mobility is not practised yet, but its environmental benefits are indisputable, compared to all other modes of transport used in the cities. Besides, the existing technological options for alternative propulsion significantly increase its attractiveness.

In Bulgaria, a National research programme "Low carbon energy for transport and domestic use" was financed at the end of 2018 by the government through the Ministry of education and science. Seven universities and institutes of the Bulgarian

Academy of Sciences are involved in this programme. A team of the University of Ruse is working on the assignments related to transport. One of them is the development of a physical model of a vessel, powered by hydrogen.

4.1 Selection of Vessel

An overview of the world's existing solutions for hydrogen powered vessels has been made.

One of the successful projects, implemented in 2017 is the vessel Energy Observer, powered by solar energy and hydrogen. The ship has electric drive and uses a mixed system of renewable energy sources (solar panels, hydrogen fuel cell) and a system that produces hydrogen from sea water [22].

The vessel chosen is one of the most suitable vessel structures at this technological stage. It is powered by alternative energy obtained from the sun and hydrogen fuel cells.

When choosing a vessel to be equipped and propelled with electricity, it is necessary to analyze the regulations in the country and the constructions of the known vessels. In the Republic of Bulgaria according to the normative documents Ordinance No. 11 of 26 April 2004 on ship and ship-owners inspections [64] inland waterway vessels on inland waterways in Europe and ships sailing between ports and facilities in the Republic of Bulgaria, fishing vessels, as well as non-commercial vessels are not subject to compliance assessments in respect of shipboard living and working conditions under the Maritime Labor Convention, 2006. Besides, according to Ordinance 22 of 11 October 2018 for the requirements for inland waterway vessels [65] vessels less than 20 meters in length and ferries are not subject to control. Furthermore, the vessel need not be registered for commercial activity. This shows that a vessel that can be designed to operate using electricity and tested in real conditions on the Danube River must meet the specified requirements. Such a vessel was constructed under the project "Clean access to the border area Calarasi—Silistra" [28]. This is a prototype vessel "trimaran" powered by electricity, Fig. 15. The vessel is 8.5 m long, 4.5 m wide and 2.5 m high. The drive consists of two electric motors of 5 kW each, operating with a voltage of 48 V. The power supply consists of two lithium batteries (LiFePO4) at 180 Ah. Solar panels with power of 5 kW are used to charge the batteries. The panels are laid over the entire surface of the vessel and are made of poly-silicon (Poly—Si). Each panel has a power of 250 W. The vessel has a weight of 1500 kg and is built to be able to carry 10 people plus a 2-person crew. The planned speed is 10 km/h and drafting depth up to 0.5 m. In the calculation of resistance and the necessary power of the vessel the forces of resistance from the weight of the container, the river on which it will sail, the water resistance of the draft.

The vessel's equipment includes: a hybrid inverter/charger with ON/OFF operation grid; LED lighting for navigation and lighting on deck with a total installed power of 200 W; electric outboard motors complete with controllers and lever system

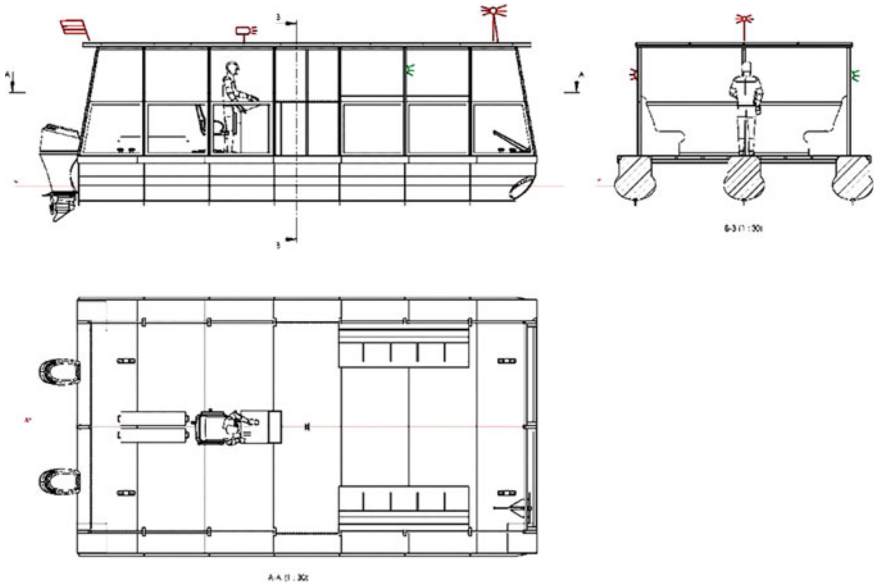


Fig. 15 General appearance of the vessel powered by electric power

for simultaneous remote control and own software for adjustment, monitoring and control; AIS/GPS transmitter for traffic control and positioning; a grid link between AC and DC consumers with protection and management; tablet docking station with a GPRS connection and the ability to supply free WIFI, equipped with software programs ONLINE/INTIME monitoring, measurements of energy consumption, operating time, distance, recording of data, setup and management of individual systems. The vessel is suitable for non-commercial purposes, such as amusement rides along the Danube and other navigable rivers, other inland waterways such as lakes and dams. When used for commercial purposes it can replace a ferry between the two banks of the river Danube, which is about 1 km in the Bulgarian-Romanian section or another necessity where the distances between the sites are shorter.

4.2 Research Methodology

The study was conducted in the Lower Danube area around the town of Silistra. The research was conducted during the summer season (July and August) of 2018 when the sun is high, because battery charging is done only by solar panels. Three routes were selected for the research, like in [8]: Route I—a 1.3 km long section in the Silistra-Kichu section; Route II—average length of 5 km in the region of Silistra—Danube Park; Route III—relatively 13 km long in the Silistra—Chatepee area. The test was made on all three routes downstream and upstream. Typically, the average velocity of flow of the River Danube in the area around Silistra is about 3.6 km/h, varying in the range of 2–6 km/h. The depth of draft of the vessel is around 0.37 m.

The tests were conducted with charged batteries. For this study the data is recorded with index 1 for sailing upstream and with index 2 the for sailing downstream: routes I, II or III; travel time $t_{1,2}$, min; distance traveled $L_{1,2}$, km; the energy consumed $E_{1,2}$, kWh; maximum speed v_{max}, km/h; maximum engine load, where the average speed on the route $v_{1,2}$, km/h, using method [20] and the energy consumption per 100 km distance traveled $Q_{1,2}$, kWh/100 km. Energy consumption for 100 km route is determined by dependence

$$Q_{1,2} = 100 * E_{1,2}/L_{1,2}\,\text{kWh}/100\,\text{km}, \quad (1)$$

where index 1 shows values for movement upstream, and index 2—downstream.

The vessel's hardware and control equipment are used for measuring and recording of the data. The management of the vessel is carried out by a qualified captain and one assistant. In the research, the total number of passengers is 5 people. The vessel is not loaded with other passengers and additional cargo.

4.3 Experimental Studies on the Danube River

During the tests with the vessel on the Danube River, the data was measured by the system embedded in Hybrid Solar Dispatcher HSD-5K-48V MPPT and Voltronics for recording data. Recording the measured values is every 60 s. The measurement accuracy is as follows: electric current ±1 A; voltage ±1%; power ±1 kW; the distance covered and velocity are measured and specified by the GPS installed. It has next technical specifications: accuracy: 0.1 km/h, update rate: 20 Hz, minimum velocity: 0.1 km/h, resolution: 0.01 km/h, latency: <41.5 ms, distance accuracy: 0.05% (<50 cm per km), 2D position ±2.5 m.

The data for the distance covered are recorded simultaneously also by the mandatory for ships Automatic identification system (AIS) installed. It allows the presentation of the route on the river map later, in order to visualize it when the direction of sailing is determined.

To determine the energy consumption, 20 attempts on three routes have been made. These results are presented in Table 10 for the upstream movement and Table 11 for the downstream movement. In the tables, 19 attempts are presented, because one of the 20 attempts are to determine the maximum flow rate of the vessel downstream. The maximum speed that is obtained when driving downstream is 14 km/h. When driving the trimaran on the selected routes, the engine load on the upstream movement is maintained within a current range of about 80 A at a maximum value of 100 A. In the downstream movement, current values are about 30 A, the goal for this experiment is not to reach maximum speed at maximum load but to maintain speeds close to the set speed of 8–9 km/h and possibly lower energy consumption and longer mileage with one battery charge.

Table 10 Test results against upstream

No. of experiment	Travelled distance, L_1 (km)	Travelled time, t_1 (min)	Travelling speed, v_1 (km/h)	Energy consumed, E_1 (kWh)	Energy consumed per 100 km, Q_1 (kWh/100 km)
Route I. Silistra—Kichu section					
1	1.35	10.32	7.85	1.376	101.93
2	1.3	9.66	8.07	1.288	99.08
3	1.29	9.9	7.82	1.32	102.33
4	1.32	10.38	7.63	1.384	104.85
Route II. Silistra—Danube Park region					
5	5	41.46	7.24	5.528	110.56
6	4.9	40.8	7.21	5.44	111.02
7	5.1	40.2	7.61	5.36	105.10
8	5.2	37.8	8.25	5.04	96.92
9	5.1	41.16	7.43	5.488	107.61
10	4.9	35.88	8.19	4.784	97.63
11	5.1	40.68	7.52	5.424	106.35
12	4.9	34.98	8.40	4.664	95.18
13	5.1	36.18	8.46	4.824	94.59
14	5	35.58	8.43	4.744	94.88
15	5	38.88	7.72	5.184	103.68
16	4.9	36.12	8.14	4.816	98.29
17	4.8	40.26	7.15	5.368	111.83
18	4.9	40.98	7.17	5.464	111.51
Route III. Silistra—Chatepee area					
19	12.83	90.42	8.51	12.056	93.97

Test results were processed in Microsoft Excel with the Descriptive module Statistics and are presented in Table 12.

After processing the data, the average energy consumption per 100 km traveled distance along Route I upstream is 102.04 kWh/100 km at an average speed of 7.84 km/h. Route II has a corresponding energy consumption of 103.23 kWh/100 km at an average speed of 7.78 km/h. On Route III the value is only one corresponding power consumption of 93.97 kWh/100 km at an average speed of 8.51 km/h. Overall, the average cost of energy is 103 kWh/100 km when sailing upstream, except Route III, which is mainly due to the lower flow velocity and more favorable conditions of sailing due to the greater length of the minutes route.

After processing the results in Excel, the average energy consumption per 100 km traveled distance along Route I in Danube river is 42.68 kWh/100 km at an average speed of 7.61 km/h. Route II has an energy consumption of 39.34 kWh/100 km at

Table 11 Downstream test results

No. of experiment	Travelled distance, L_1 (km)	Travelled time, t_1 (min)	Travelling speed, v_1 (km/h)	Energy consumed, E_1 (kWh)	Energy consumed per 100 km, Q_1 (kWh/100 km)
Route I. Silistra—Kichu section					
1	1.35	10.80	7.50	0.58	42.67
2	1.31	11.00	7.15	0.57	43.72
3	1.33	10.30	7.75	0.57	43.91
4	1.34	10.00	8.04	0.53	40.40
Route II. Silistra—Danube Park region					
5	5.03	34.20	8.82	1.82	36.48
6	5.05	38.60	7.85	2.06	42.01
7	5.02	40.40	7.46	2.15	42.25
8	5.28	39.30	8.06	2.10	40.31
9	4.92	33.70	8.76	1.80	35.24
10	5.0	34.50	8.70	1.84	37.55
11	5.03	37.80	7.98	2.02	39.53
12	5.1	33.70	9.08	1.80	36.68
13	5.02	39.80	7.57	2.12	41.62
14	4.89	34.20	8.58	1.82	36.48
15	5.07	35.50	8.57	1.89	37.87
16	4.96	36.00	8.27	1.92	39.18
17	5.07	40.50	7.51	2.16	45.00
18	5.03	37.30	8.09	1.99	40.60
Route III. Silistra—Chatepee area					
19	12.91	100.20	7.73	5.01	39.05

an average speed of 8.24 km/h. On Route III the value of energy consumption is 39.05 kWh/100 km at an average speed of 7.73 km/h. Overall, the average cost of energy is 40 kWh/100 km at an average speed of 8 km/h for downstream movement.

When processing all of the results from the routes, we conclude that the average energy consumption when travelling upstream is 102.49 kWh/100 km at an average speed of 7.8 km/h, Table 12. The average power consumption when travelling downstream is 40.03 kWh/100 km at an average speed of 8.08 km/h.

In linear reversible routes, which include sail in both directions of the current, the average power consumption is obtained for Route I—71.9 kWh/100 km, for Route II—71 kWh/100 km and Route III—66.5 kWh/100 km. For all the results, the average energy consumption is 71.3 kWh/100 km at an average speed of 7.95 km/h, Table 12. This shows that with increasing distance travelled, energy consumption reduces. It means that options for conservation and creation of energy for the vessel so that it can

Table 12 Characteristics values of the surveyed route metrics

Value	Metrics					
Tested indicators	v_1 (km/h)	Q_1 (kWh/100 km)	v_2 (km/h)	Q_2 (kWh/100 km)	v_{12} (km/h)	Q_{12} (kWh/100 km)
Mean	7.8316	102.49	8.0768	40.029	7.954	71.260
Standard error	0.108	1.4225	0.1257	0.6497	0.084	5.192
Median	7.82	102.33	8.0400	40.3077	7.917	69.485
Mode	#N/A	#N/A	#N/A	36.48	#N/A	36.480
Standard deviation	0.4709	6.2003	0.5478	2.8321	0.519	32.005
Sample variance	0.2217	38.444	0.3001	8.021	0.269	1024.3
Kurtosis	−1.3975	−1.363	−0.9665	−0.9825	−0.816	−2.012
Skewness	−0.0287	0.1497	0.2246	0.0256	0.217	0.045
Range	1.36	17.86	1.9347	9.7582	1.935	76.588
Minimum	7.15	93.97	7.1455	35.2418	7.145	35.242
Maximum	8.51	111.83	9.0801	45	9.080	111.83
Sum	148.8	1947.3	153.459	760.555	302.3	2707.9
Count	19	19	19	19	38	38

travel longer distances for longer periods of time without stopping should be sought. The decision to increase the number of batteries is not desirable because it costs a lot and increases the weight of the container. The option of using solar energy is good, but only under certain conditions, which does not allow a complete solution to the issue. A suitable option is the use of a hydrogen fuel cell power generation system and a hydrogen generation system on board of the vessel from pure water, similarly to the vessel in [22]. Therefore, the results of the survey, as well as the created vessel, can be used for improvement purposes, with the addition of a hydrogen fuel system to increase the length of the voyage.

In the case of distances up to 15 km, the trimaran and any other similar vessel requiring electricity are quite suitable for recreation and development. People who sail with trimaran have the opportunity to fish, race, etc. In this case the vessel is used for commercial purposes, it is well put to be used as a ferry boat for transportation from one river shore to the other.

5 Multicriteria Optimisation of Urban Public Transport

In Fig. 16, the line graph illustrates the process of passenger movement through the urban public transport, reflecting the main structure of movement in the transport

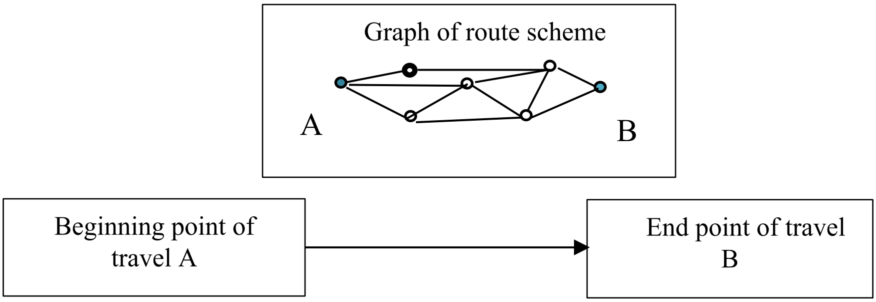


Fig. 16 Line graph of the process of passenger movement through the urban public transport

network from point A to point B. The apexes of the graph are the stops of public transport and the edges are its routes.

The passenger needs to move from starting point A (public transport stop) to end point B (public transport stop). In doing so, he can choose both different routes (incl. transfer), and different vehicles (bus, trolley bus, tram, underground) along individual sections of the route. The route and the vehicles can be selected according to various criteria. Such tasks are best described with the theory of graphs and are often modelled as tasks of linear/non-linear programming, integer, continuous and partially integer optimization [66]. With more than one criterion, the task becomes multicriteria one.

This paper deals with the task of finding the optimal route for passenger movement, using two main criteria:

- minimising the movement time;
- least harmful emissions.

For this purpose, the transport scheme of a particular location is viewed as an oriented graph, where each bus stop is a node, and each route connecting a given stop *No.* i, to another stop *No.* j, is an oriented weighted edge (i, j) in the graph. This weight of the edge c_{ij} is directly related to the selected criteria. In the case of each directed edge, two weights will be initiated for each vehicle with number k, passing along the edge, where travel time is c_{ij}^{k1}, and the harmful emissions (in conventional units) c_{ij}^{k2} along the given edge (i, j). If k vehicles pass between two stops, k weights are initiated under both criteria—$c_{ij}^{11}, c_{ij}^{21}, \ldots, c_{ij}^{k1}$; $c_{ij}^{12}, c_{ij}^{22}, \ldots, c_{ij}^{k2}$. It is clear that under both criteria there are weights $c_{ij}^{k_1 1}$ and $c_{ij}^{k_2 2}$, which will be the smallest under the respective criterion—$c_{ij}^{k_1 1} \leq c_{ij}^{1l}, c_{ij}^{k_2 2} \leq c_{ij}^{2r}, \ \forall l, r = \overline{1, \ldots, k}$. The vehicle with the smallest expense (value) between two stops according to a given criterion will be called dominating under this criterion between these particular apexes. When one criterion is set, it is appropriate to consider only the dominating vehicles between two stops for carrying out the transportation. To simplify the task, it is assumed that only two vehicles move along each edge. Thus, for each edge (i, j), the weights initiated are $c_{ij}^{11}, c_{ij}^{12}, c_{ij}^{21}\ c_{ij}^{22}$. In this way there are two options for selecting a vehicle between two stops (i.e. two apexes in the graph)—one is dominating in time and the other—in harmful emissions (it is possible one and the same vehicle to be dominating in both criteria simultaneously). If only one criterion is followed, the task becomes classical one for finding the shortest route in a graph, for which there are several algorithms known—algorithm of Dijkstra, algorithm of Ford-Bellman, etc. When there are two or more criteria, the task refers to multicriteria optimisation. With two or more criteria, it is common initially to solve the task as single criterion—for each separate criterion. The formulation and the mathematical model (single-criterion) for a task about "the shortest route" in a oriented graph can be described as follows:

An oriented weighted graph with n nodes and adjacency matrix C with weight (expense under one given criterion) c_{ij}, is given along the oriented edge (i, j). If there is no directed edge, connecting node i to node j, i.e. there is no vehicle providing transportation under the given criterion, then we have $c_{ij} = M$, where M is a very big number—$M \gg 1$. We look for "the shortest route" (in terms of the given criterion) between 1st node and the nth node (we can always number the starting node *No.* 1, and the end node *No. n*).

The task for the shortest route between two nodes is defined in terms of linear integer optimisation in the following way:

$$\min Z = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{2}$$

$$\sum_{i=1}^{n} x_{ik} - \sum_{i=1}^{n} x_{ki} = 0, \quad \forall k = \overline{2, \ldots, n-1} \tag{3}$$

$$\sum_{i=2}^{n} x_{1i} = 1 \tag{4}$$

$$\sum_{i=1}^{n-1} x_{in} = 1 \tag{5}$$

$$x_{ij} \in \{0, 1\} \tag{6}$$

The binary variable x_{ij} (6) adopts value 1, if the route passes along edge (i, j) from node i to node j and 0 otherwise. Condition (2) expresses a criterion set for minimizing of the total costs from the beginning of the route to its end. Restrictions (4) and (5) refer to the selection of exactly one node to get to from the starting node, and respectively, exactly one node, from which to get to the end node. Restriction (3) refers to all the remaining nodes and sets the condition that the sum of all incoming vehicles for a given interim node should be equal to the sum of all outgoing vehicles.

Various matrices can be assigned as adjacency matrices $C^{k1}, C^{k2}, \ldots, C^{km}$, describing a particular expense of kth vehicle along the respective edges. The adjacency matrices are assigned depending on the criterion set—a criterion for minimum total travel time, one for minimum total travel cost, another for minimum total amount of harmful emissions during travelling, etc. With two criteria set and two vehicles, Z_1, Z_2 denote the expenses on the first and the second criterion, respectively. c_{ij}^{11}, c_{ij}^{12} denote the expenses of the first vehicle on the first and the second criterion, respectively, along the edge (i, j). Likewise, c_{ij}^{21}, c_{ij}^{22}—denote the expenses of the second vehicle. Then

$$Z_k = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij}^{1k} x_{ij}^1 + c_{ij}^{2k} x_{ij}^2, \quad k = 1, 2 \tag{7}$$

are the total expenses under the two criteria.

The problem comes down to minimizing the vector criterion

$$\begin{aligned} Z &= [Z_1(x), Z_2(x)] \\ x &= (x_{11}, x_{12}, \ldots, x_{nn}). \end{aligned} \tag{8}$$

With restrictions

$$\sum_{r=1}^{2} \left(\sum_{i=1}^{n} x_{ik}^r - \sum_{i=1}^{n} x_{ki}^r \right) = 0 \quad \forall k = \overline{2, \ldots, n-1}, \tag{9}$$

$$\sum_{r=1}^{2} \sum_{i=2}^{n} x_{1i}^r = 1, \tag{10}$$

$$\sum_{r=1}^{2} \sum_{i=1}^{n-1} x_{in}^r = 1, \tag{11}$$

$$\sum_{r=1}^{2} x_{ij}^r \leq 1, \tag{12}$$

$$x_{ij}^r \in \{0, 1\}. \tag{13}$$

Here the unknown variable x_{ij}^r (13) adopts value 1, if the route passes along edge (i, j) from node i to node j with rth vehicle, and 0 otherwise. Restrictions (10) and (11) refer to the selection of exactly one node and one vehicle to get to from the starting node, and respectively, exactly one node and one vehicle, from which to get to the end node. Restriction (9) has the same meaning as restriction (3). Condition (12) refers to the fact that only one vehicle can travel along a given edge in one direction. The problem thus set (8)–(13) is a task of the multicriteria integer linear optimising. This leads to the following two difficulties: the criteria (target functions) are more than one and the solution should be integer one (in this case—binary variables). Concerning the multicriteria, there are a few remarks [67, 68]. Selecting a limited number of most important criteria from the set of real-world identifiable possible characteristics of the object to be optimized is always a special kind of art.

Another characteristic feature of multicriteria tasks is the lack of a single optimal solution. Usually, the result from their solution is a set of the so-called Pareto-optimal solutions, obtained with the help of the principle of consistent optimality, suggested by Vilfredo Pareto [69]. As none of those solutions is better than the others (unless further considerations are taken into account), it is advisable to find as many Pareto-optimal solutions as possible. This widens the area from which a suitable choice of a feasible solution can be made by taking into account the specific features of the problem being solved. Identifying such an unambiguous solution under many and contradictory criteria always requires further information and to some extent reflects someone's subjective idea of a compromise. The choice of a compromise solution, unlike the scientifically justified determination of the set of Pareto-optimal solutions, requires the individual (or sometimes a team of specialists or experts) making the decision to have experience, intuition and informal knowledge of the optimization problem.

There are two main goals in the multicriteria optimisation:

- to find solutions close to the real-world Pareto-optimal ones;
- the solutions identified to be substantially different from one another and one of them to be chosen eventually.

Achieving the first goal means that the conditions for consistency are met, and achieving the second—that there is no mixing of different criteria.

With this kind of optimization, several target functions, usually written as elements of a vector, called vector criterion, have to me minimized (maximized). The task for vector optimization contains restrictions on the parameters, so that its general formulation is as follows:

$$opt_{x \in X} Z(x) \tag{14}$$

$$Z(x) = [Z_1(x), Z_2(x), \ldots, Z_m(x)]^{\mathrm{T}}, \tag{15}$$

$$X \equiv \{x \in \Pi \subset E^{\mathrm{n}}: g_i(x) = 0,\ j = \overline{1, \ldots, s};\ g_i(x) \leq 0,\ j = \overline{s+1, \ldots, r}\} \tag{16}$$

$$\Pi \equiv \left\{x \in E^n: x^- \leq x \leq x^+\right\}. \tag{17}$$

The operator "opt" of (14) means consistent optimality of all criteria. Without losing the set, it is assumed that they require minimising. In Fig. 17, the sets of Pareto-optimal solutions are shown.

Point D is optimal under the first criterion, point C—under the second, while the points from the borderline CD, Fig. 17 and their corresponding points from the parametric space form the sets of Pareto-optimal solutions (the sets of infallible, effective, non-dominant, compromise solutions). The definition of the term consistent optimality is based on the principle of Pareto-optimality: The control vector $\bar{x} \in X$ is Pareto-optimal (infallible, non-dominant, effective), if there is no other control vector $x \in X$, for which

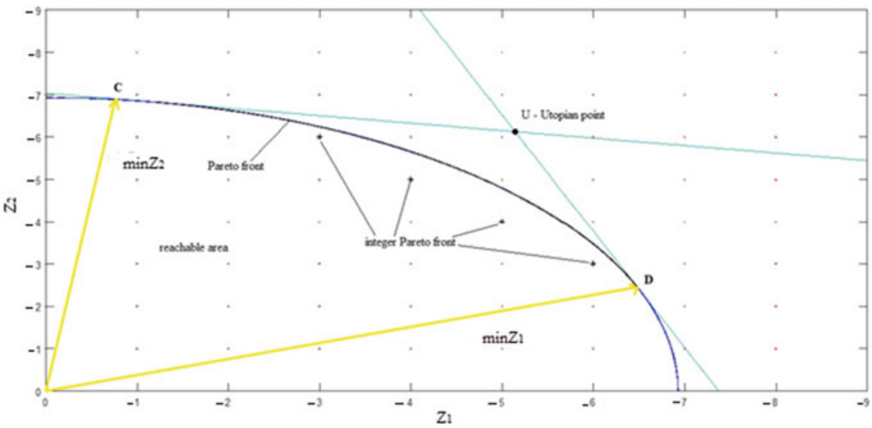


Fig. 17 Points from the sets of Pareto-optimal solutions

$$Z_r(x) \leq Z_r(\bar{x}),\ r \in \{1, 2, \ldots, m\}, \tag{18}$$

As the inequality is strict $Z_\nu(x) < Z_\nu(\bar{x})$ at least for one of the criteria Z_ν.

Similarly, the vector criterion $\bar{f} = Z(\bar{x})$, $\bar{f} \in F \equiv \{f \in E^m\colon f = Z(x), x \in X\}$ is Pareto-optimal if there doesn't exist another criterial vector $f \in F$, for which $f_r \leq \overline{f_r}$, with a strict inequality ($f_\nu < \overline{f_\nu}$) at least for one of the criteria f_ν.

It is said that the vector criterion $\bar{f} = Z(\bar{x})$ is definitely better than criterion $\tilde{f} = z(\tilde{x})$, if Pareto's rule is satisfied (18) for $\equiv \tilde{x}$. This fact is noted briefly like this: $\bar{f} \succ \tilde{f}$. The same notion is also valid for the parametric space, i.e. $\bar{x} \succ \tilde{x}$. The points forming the Pareto-optimal set are incomparable to one another. For example, it is not possible to prefer one of the points $C\left(Z_1^C, Z_2^C\right)$ and $D\left(Z_1^D, Z_2^D\right)$ from the borderline CD of the achievable set in Fig. 16, because $Z_1^C > Z_1^D$, but $Z_2^C < Z_2^D$. The same refers to the remaining points from the borderline CD, which is called compromise line in the two-dimension case. The Pareto-optimal solution of a problem (14) means the corresponding sets of Pareto-optimal points in the criterion and parametric spaces. In order to recognize more easily the Pareto-optimal points in the two spaces, some authors [70, 71] use the term effective points (effective set) only for the allowable set, while the label Pareto-optimal points (Pareto-optimal set)—only for the achievable set. It must be taken into consideration that the Pareto-set can be either locally or globally optimal. Strict definition of these notions are provided in [72]. The explicit indication of the meaning that interprets the term optional, is required by the fact that different principles for optimality have been introduced in the theory of vector optimisation, for example of: Geoffrion (G), Borwein (B), Pareto (P), Sleiter (S) [73]. To get a general idea of the difference between them, the sets of optimal solutions, determined under these principles, are indicated by the symbols, given in the parentheses. Then the ratio between these sets is of the type $G \subseteq B \subseteq P \subseteq S$. Point U, which corresponds to the non-compromise minimums of the particular criteria, is called utopian point (ideal point). In the case illustrated in Fig. 17 (as is the case with conflict criteria) it is unrealizable because it is in the area, which is out of reach. In some of the algorithms for multicriteria optimisation point U is used as an ideal goal.

If the criteria are unambiguous functions, only one point of the achievable criterion set corresponds to each point from the admissible parametric set. In general, though, different points in the admissible set correspond to one point of the achievable set. This mutual ambiguity requires a sufficiently comprehensive and accurate study of both sets. The internal points of the achievable area are not of interest for the optimisation since for them improvement of all criteria is possible. It is important to generate a sufficiently complete and accurate Pareto-optimal set, from which to make an appropriate choice of one solution. In a number of cases, building the entire Pareto-optimal set is difficult to accomplish. Then the vector criterion is scalar with the help of a selected compromise scheme. In this way, the multicriteria tasks is transformed into a task for global optimisation with a scalar criterion and different methods can be used for solving it. In this case, however, a subjective element is introduced in the optimisation process. Besides, replacing the vector criterion with a scalar one is a complex problem that cannot always be solved. Sometimes this approach can generate pseudooptimal solutions, which illustrate very well the obvious gap between what can be achieved and what has been achieved.

Generally, the existing methods for multicriteria optimisation can be divided into two groups:

1. Methods based on optimizing a generalized criterion, identified within a pre-selected compromise strategy [72, 74, 75].
2. Methods based on identifying an approximate Pareto-optimal set [70, 71, 76, 77]. Some of them are:

Weighting Method

The method offered by L. Zadeh in 1963 implements a linear compromise scheme [72, 78]. The multicriteria task is transformed into single-criterion one with the help of a linear combination from the separate criteria with pre-selected coefficients w (weighted coefficients):

$$\min_{x \in X} \quad Z(x), \tag{19}$$

where $Z(x) = \sum_{r=1}^{m} w_r Z_r(x)$ is the generalized criterion of Zadeh, and X is the admissible set of controlling parameters.

Usually the coefficients w are considered to be estimates of the significance of each criterion. Then they have to satisfy:

$$w_r \geq 0, \ \sum_{r=1}^{m} w_r = 1.$$

Their choice is subjective. The weighted compromise scheme is used for criteria with similar dimensions. Otherwise, they are normalized in advance.

To solve task (19) we can use one of the known methods for single-criterion optimisation. The problem is in the choice of weighted coefficients. Their values do not correspond directly to the relative significance of the criteria and do not allow to express compromise ratio between the target functions in the different compromise situations. Besides, in some cases, some of the Pareto-optimal solutions become inaccessible (if the Pareto set is not convex).

A Method of ε-Restrictions

This procedure, proposed by Haimes, Lasdon, Wismer in 1971 [72, 78], overcomes the flaws of the weighted methods, due to the fact that the Pareto set is not convex. With this compromise scheme, one of the criteria, for example $Z_\mu(x)$, is chosen to be the main one and is minimized while the remaining criteria are assumed to be restrictions of the type

$$Z_r(x) \le \varepsilon_r,\ r = \overline{1, m}, \quad \mu \ne r. \tag{20}$$

The method allows to determine Pareto-optimal solutions along a section that is not convex as well. Using this method, it is problematic to determine the main criterion Z_μ and to select appropriate values of the vector components $\varepsilon = [\varepsilon_1, \ldots, \varepsilon_\nu, \ldots, \varepsilon_m]^{\mathrm{T}},\ \nu \ne \mu$, which provide admissible solution. The possible sharp variations in the criteria values are an obvious flaw.

A Method of Achieving the Goal

This method involves setting a goal$^\circ = \left[z_1^\circ, \ldots, z_m^\circ\right]^{\mathrm{T}}$, which corresponds to criterion $(x) = [Z_1(x), \ldots, Z_m(x)]^{\mathrm{T}}$. The formulation of the task allows to approach the goal in two ways—from the bottom (with lower values of criteria Z_r from the components z_r° of the goal), or from the top (with higher values). The process is controlled by a weighted vector $= [w_1, w_2, \ldots, w_m]^{\mathrm{T}}$. The task for vector optimisation (19) is transformed into single-criterion task of the type [78]:

$$\min\nolimits_{\gamma, x \in D} \gamma, \tag{21}$$

where

$$D\left\{\gamma \in E^1, x \in E^n : x \in X,\ Z_r(x) - w_r\gamma - z_r^\circ \le 0,\ r = \overline{1, m}\right\}. \tag{22}$$

The value γ is a scalar, and the presence of the addend $w_r\gamma$ allows some freedom in approaching the goal. The weighted vector w allows the introduction of a measure for the relative compromise between the goals. For example, laying $w = z^\circ$ means that an equal relative approximation of $Z_r\ z_r^\circ$ is achieved. If we accept $w_r = 0$, the respective criterion will satisfy the strictly recommended restriction. In the process of optimisation the value γ is changed and the size of the accessible area is changed at the same time.

A Minimax Method

To avoid cases of unacceptably bad values of some criteria, it is appropriate to include criteria restrictions in the structure of the vector optimisation task (19)

$$Z_r(x) \le z_r^+, r \in r = \overline{1, m}, \tag{23}$$

Limit values of private criteria Z_r are given to z_r^+. In [79], the following approach for determining a single Pareto-optimal solution has been proposed: with the help of vectors $Z(x)$ and $z^+ = \left[z_1^+, \ldots, z_m^+\right]^{\mathrm{T}}$ a scalar function is defined

$$\alpha(x) = \max_r \left\{ \frac{Z_r(x)}{z_r^+} \right\}, \quad r = \overline{1, m}. \tag{24}$$

It is appropriate that the choice of limit values is subject to the requirement $\alpha \le 1$. The optimal solution in

$$_{\mathrm{x} \in \mathrm{X}} \alpha(x) \equiv \min_{x \in X} \max_r \left\{ Z_r(x)/z_r^+ \right\} \tag{25}$$

Of the scalar optimisation tasks is a Pareto-optimal solution of the original task (19). If $\alpha^* \le 1$, the solution is satisfactory.

A Method of Global Criterion

With the method of global criterion the distance between some set point $z^\circ = \left[z_1^\circ, z_2^\circ, \ldots, z_m^\circ\right]^{\mathrm{T}}$ in the criterial space and the points of the achievable set is minimised. Usually the utopian point U is chosen to be point $^\circ$. In this case, task (19) is transformed to

$$\min_{x \in X} d(x), \tag{26}$$

where

$$(x) = \left(\sum_{r=1}^{m} w_r \left[Z_r(x) - z_r^\circ \right] \right)^{\frac{1}{p}}. \tag{27}$$

If all criteria are equally important, the weighted coefficients are assumed to be equal $w_r = 1$. With $p = 1$ the general criterion (27) is a linear combination of the vector components $|Z(x) - z^\circ$. The value d for $p = 2$ coincides with the distance between two points of the r-dimensional Euclidean space. Quite often instead of d the square d^2 of distance is used. The compromise scheme obtained in this case was used for the first time in 1971 by Salukvadze [80]. The solution obtained under this scheme is called optimal solution by Salukvadze. It is Pareto-optimal and brings all private criteria $Z_r(x)$ equally close to their ideal values z_r°. For $p = \infty$ general criterion is obtained

$$\min_{x \in X} \max_{r=\overline{1,m}} \left\{ w_r \left[Z_r(x) - z_r^\circ \right] \right\}. \tag{28}$$

Corresponding to the compromise scheme of P. Chebyshev [72]. The compromise solutions, obtained for different values of p, can differ substantially. The most widely used application in optimisation practice is the compromise scheme of Salukvadze. A major disadvantage of Salukvadze's scheme is the need to determine in advance the utopian point, which is unique for each multicriteria task.

A Method with a Non-linear Compromise Scheme

The compromise scheme proposed by Voronin [74], reduces task (19) to a single criterion one

$$x^* = \arg\min_{x \in X} \sum_{r=1}^{m} z_r^+ \left[z_r^+ - Z_r(x) \right]^{-1}, \tag{29}$$

where limit values for private criteria are given to z_r^+. The value

$$\rho_r = 1 - Z_r(x)/z_r^+ \tag{30}$$

can be seen as a measure of closeness of rth relative criterion to its limit value (in this case 1), while the value $1/\rho_r$ characterizes the "strain" of the compromise situation, corresponding to the level achieved under this criterion $Z_r(x)$. The general Voronin criterion

$$Z(x) = \sum_{r=1}^{m} 1/\rho_r \tag{31}$$

has adaptive properties for various "strain" of the compromise situations, depending on the value of addends $1/\rho_r$. When the value of some of the private criteria starts getting closer to its limit (strained compromise mode), the criterion Z increases sharply and the minimizing of the whole sum is reduced to minimizing of the worst addend. Then the scheme becomes minimax. If private criteria are far from their limit values (calm compromise mode) the scheme realizes the principle of integral optimality. In intermediate situations, partial alignment of relative criteria is carried out to varying degrees (the principle of consistent optimality is realised).

PSI-Method

PSI-method (short for Parametric Space Investigation) is at the heart of a universal computing technology for solving applied multicriteria tasks for optimal design of technical objects and processes [70, 76]. It combines the ability to probe effectively multidimensional sets with quasi-evenly distributed Sobolev points and the study of the change of all criteria in kind for the whole allowable set of control parameters. In order to use the PSI-method, we need a mathematical model—simulator of the optimizable object, where, besides the usual non-linear optimisation constraints, variable restrictions on changing the criteria may also ne introduced. Thus expended, the optimisation task requires the formation of the admissible parametric set to take place during the process of solving the optimisation task. The software based PSI-method offers [81]:

- information for the intervals of changing the individual criteria;
- varying the control parameters depending on the restrictions imposed;
- possibility of a rational choice of regional and criterion restrictions;
- possibility for interpreting restrictions as pseudo-criteria;
- dialogue mode for decision-making by the approximate Pareto-optimal set;
- ability to highlight dependent criteria;
- spreadsheet layout and easy sorting of results by various indications. The PSI-method has been described in details in [70, 71, 76, 77]. Information about the computational technology can be accessed on the Internet site [81].

Task (8)–(13) is reviewed again. A goal is set to find Pareto-optimal solutions. The vector criterion (8) is linear and the restrictions (9)–(12) care linear too, which means that the admissible set is convex. Condition (13) is one of integer variables (or at least some of them should be integers). Imposing a condition on variables to be integers leads to additional difficulties in finding a solution. These are tasks of the so-called class NP-complexity (nondeterministic polynomial time). The Pareto-optimal solutions in this case are the discrete set in Fig. 17 and it is not obligatory the points to coincide with points from the Pareto-optimal solutions without the condition for integers. It should also be noted that on Fig. 17 a discrete Pareto-front of the achievable area is given. These points are not necessarily integers—they reflect the criteria values. It is the coordinates of points from the admissible area that are integers.

Taking into consideration the fact that the admissible area is a convex set, in order to find the Pareto-optimal solutions under the conditions of integer variables, it is quite appropriate to apply the weighting method proposed by L. Zadeh. A generic criterion is constructed as a linear combination of the private criterion with weights λ^r, $r = 1, 2$ and condition for the weights

$$\sum_{r=1}^{2} \lambda^r = 1, \lambda^r \geq 0, \;\; r = 1, 2. \tag{32}$$

The weights λ^r are given evenly distributed random numbers, which satisfy the condition (32) (the area set with (32) is probed). For each random set of weights, a single-criteria integer task is solved

$$\min Z = \lambda^1 Z_1 + \lambda^2 Z_2 = \sum_{r=1}^{2} \lambda^r Z_r = \sum_{r=1}^{2} \lambda^r \sum_{i=1}^{n} \sum_{j=1}^{n} (c_{ij}^{r1} + c_{ij}^{r2}) x_{ij}^r \tag{33}$$

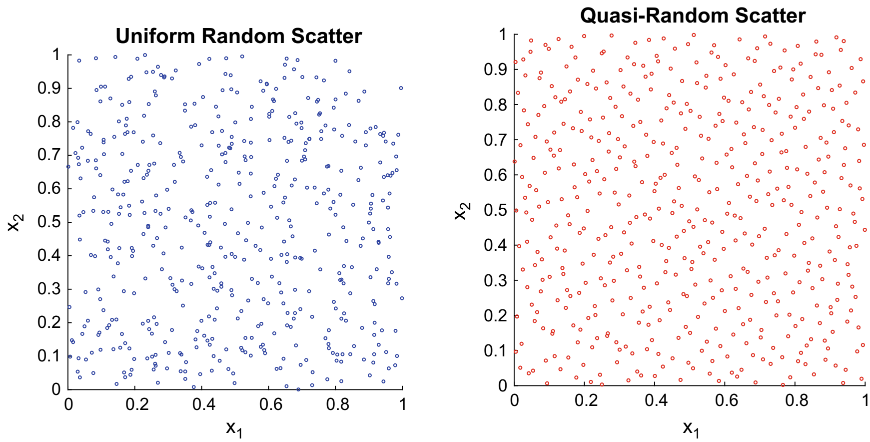
under conditions (9)–(13). The different solutions are selected. They form Pareto-optimal solutions for integer variable coordinates (control parameters).

For larger dimensions of the integer optimisation task (33), the time and memory for its solution grow fast. The task is solved repeatedly by randomly generated vector weights (a randomly selected point in the area (32)). It is appropriate the random generation to be selected in a specific way the goal being to achieve greater efficiency in finding Pareto-optimal solutions with fewer attempts. To this end, a quasi-uniform probing is applied.

This is a systematic scanning of a multidimensional parametric area with a quasi-evenly scattered series of probing points. These points are determined analogue of random points, but they have better distribution and when equal in numbers, they provide the same placement for each new numerical experiment. Although probing the allowable set D in the random search methods is also conducted with evenly scattered points, their actual location is uneven. For example, in Fig. 18 are shown an equal number of "evenly" scattered points in a square area, respectively (a)—pseudorandom and (b)—points determined by the so called "$LP\tau$-row" (Sobolev probing points) [82, 83].

The imperfection of the arrangement of the random point in Fig. 18a is due to the random fluctuations of their coordinates and to the deviation from the theoretic requirements for the uniformity of the random number generator used.

The probing variant in Fig. 18b with deterministic quasi-evenly scattered Sobolev points is better for implementation of global optimisation in multidimensional areas. It is easy to find that the projections of these points on the sides of the square (generally—on the sides of an m-dimensional cube) are evenly scattered. These points do not "shadow" each other because there are no other probing points hiding in their orthogonal "shadows". This property of theirs is the reason for their greater



(a) pseudorandom deterministic points (b) deterministic points

Fig. 18 Sobolev probing points

informativeness in probing arbitrary multidimensional areas with unequal sensitivity of the objective function to the changing of all its arguments.

In the practical generation of quasi-evenly scattered Sobolev points, it is impossible to achieve equal uniformity along all x_i coordinates of the vector x. The uniformity is higher for the control parameters with smaller index, for $i = 1$ it is the highest. In this sense, the method of deterministic probing depends on the order of numbering of the control parameters. That is why, the most significant ones should be placed in the beginning of the vector x. The theory of uniformly scattered rows (or meshes) of points is reviewed in [82, 83]. In [83–85] generators of Sobolev points are described, which can be easily embedded in optimisation procedures. The increase of dimension n of the vector x reduces the advantages of deterministic probing compared to the random one. Some authors assume that for $n > 10$ both approaches have relatively equal efficiency. It can be proven [83], that if set Π is probed with Sobolev points, those in the subset $D \supset \Pi$ also form quasi-evenly scattered series. The ration $A = V_D / V_\Pi$ of the respective volumes of n-dimensional areas D and Π determines the efficiency of the probing. This assessment provides information on the degree of difficulty of solving the optimisation task because it characterizes the number of propping points, which have to be generated in area Π, so that at least one of them gets into D.

An example is considered with adjacent matrices for the first and second vehicles, according to the two criteria respectively, presented in the following tables.

With Matlab software task (8)–(13) is solved. The input data are the adjacency matrices and the number of pseudo-random Sobolev points. For the specific data from Tables 13, 14, 15, and 16, with N = 100 Sobolev pseudo-random probing points, Pareto-optimal solutions and figures under the two criteria are given in Table 17.

In Fig. 19 is shown the graph for the example reviewed. The presence of an edge between two apexes reflects the fact that at least one vehicle passes between them.

In Table 17, four different possibilities for moving from first to seventh apex can be seen. Not one of these solutions is dominated by the others under the two criteria simultaneously. This confirms the fact that they are Pareto-optimal discrete solutions. As it was already mentioned, there are various techniques for selecting one of all the

Table 13 Adjacency matrix of weights c_{ij}^{11} between the individual apexes according to the first criterion for the first vehicle

No.	1	2	3	4	5	6	7
1	M	0.7770	0.2988	0.9390	M	M	M
2	0.7582	M	M	M	0.3411	M	M
3	0.8870	M	M	0.0014	M	0.5078	M
4	0.0688	M	0.5677	M	0.9262	0.8567	M
5	M	0.8558	M	0.0875	M	0.3843	0.2798
6	M	M	0.8429	0.2607	0.3381	M	0.4470
7	M	M	M	M	0.8595	0.6279	M

Table 14 Adjacency matrix of weights c_{ij}^{12} between the individual apexes according to the second criterion for the first vehicle

No.	1	2	3	4	5	6	7
1	M	0.7769	0.3044	0.9444	M	M	M
2	0.7577	M	M	M	0.3432	M	M
3	0.8789	M	M	0.0014	M	0.4946	M
4	0.0696	M	0.5782	M	0.9225	0.8306	M
5	M	0.8393	M	0.0882	M	0.3891	0.2764
6	M	M	0.8374	0.2560	0.3374	M	0.4492
7	M	M	M	M	0.8114	0.6068	M

Table 15 Adjacency matrix of weights c_{ij}^{21} between the individual apexes according to the first criterion for the second vehicle

No.	1	2	3	4	5	6	7
1	0.7981	0.3001	0.9168	M	M	M	M
2	0.7618	M	M	M	0.3299	M	M
3	0.8819	M	M	0.0014	M	0.5185	M
4	0.0678	M	0.5746	M	0.9216	0.8590	M
5	M	0.8839	M	0.0930	M	0.3732	0.2764
6	M	M	0.8697	0.2636	0.3311	M	0.4522
7	M	M	M	M	0.8787	0.6319	M

Table 16 Adjacency matrix of weights c_{ij}^{22} between the individual apexes according to the second criterion for the second vehicle

No.	1	2	3	4	5	6	7
1	M	0.7434	0.2995	0.9448	M	M	M
2	0.7749	M	M	M	0.3431	M	M
3	0.8963	M	M	0.0014	M	0.5058	M
4	0.0683	M	0.5654	M	0.9136	0.8529	M
5	M	0.8449	M	0.0885	M	0.3821	0.2841
6	M	M	0.8249	0.2648	0.3483	M	0.4461
7	M	M	M	M	0.8653	0.6190	M

Pareto-optimal solutions. For this specific example, the decision-making individual has been given the chance to select one of these solutions subjectively.

Table 17 Pareto-optimal solutions and values under the two criteria

Pareto-optimal solutions	Route along nodes	Edges covered by first vehicle	Edges covered by second vehicle	First criteria value Z_1	Second criteria value Z_2
1	(1, 3, 6, 7)	(3, 6)	(1, 3), (6, 7)	1.8768	1.2402
2	(1, 3, 6, 7)	(1, 3), (3, 6)	(6, 7)	1.2588	1.2451
3	(1, 2, 5, 7)	(5, 7)	(1, 2), (2, 5)	0.9098	1.3629
4	(1, 2, 5, 7)	–	(1, 2), (2, 5), (5, 7)	0.9064	1.3706

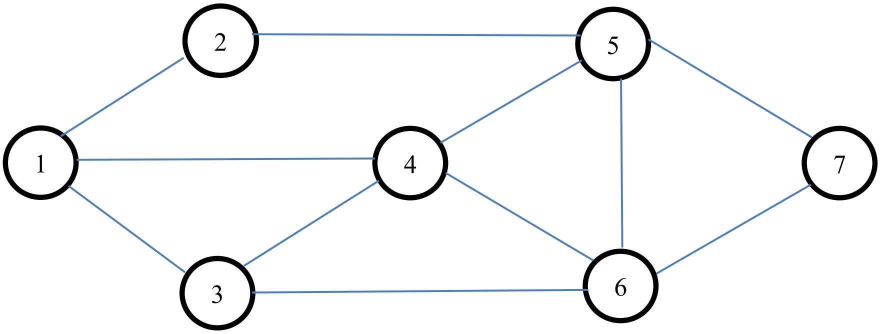


Fig. 19 A graph reflecting the connections between two apexes

6 Conclusion

1. Contemporary urbanisation, the low quality of the transport services offered by the public urban transport, the high level of air and noise pollution and the large number of accidents are a serious problem for the big cities in the republic of Bulgaria.

In 2018, the urban population in Bulgaria amounts to 5,159,129, which is 73.5% of the whole population. Public urban passenger transport is carried out by buses, trolleybuses, trams and underground (the last two only in the capital). Bus transport has the largest volume of transport operations with 346,550,000 passengers served and 3131 million pkm for 2017. In many cities it plays an important role in satisfying passenger needs for transport. The percentage of passengers served by modes of public transport is as follows: bus transport has served more than half of the passengers (55%), followed by trams with 18%, underground—15% and trolleybuses—12%. The transport fleet for public urban transport has not been upgraded as a whole. The number of cars in the country has been growing continuously. For the period of 7 years CO_2 has grown by 18%. In 2017, the carbon dioxide emissions from road transport were 8,842,106 t. Of the remaining harmful substances, for the same period—2011 to 2017—the methane increased almost twice, and so did dual nitrogen oxide and ammonia. The fine particle concentration in the cities, caused by domestic burning and industry, as well as by heavy traffic, is often above limits. There has been observed a persistent tendency to increase noise pollution in urban territories to levels in the range of 63–67 and 68–72 dB(A), while the norm is 55–60 dB(A). The total number of accidents in the country for 2017 is 6888, of which 4426 in the big cities (64.25%).

2. Four major stages of evolution of urban mobility in the second half of the 20th century in Bulgaria can be defined: stage 1—characterised by an interest in increasing automobile ownership and expanding the transport infrastructure of cities; stage 2—stimulating the use of public transport, at the expense of reducing automobile use and securing infrastructure for this; stage 3—a sharp increase in the number of private automobiles, most of which are too old and thus, increasing the automobile traffic load in cities; stage 4—promoting sustainable travel and alternative forms of travelling in cities.
3. Of 257 cities in the Republic of Bulgaria, by 2019 only 12 have plans for sustainable urban mobility developed, i.e. only 4.6%.
4. Based on observations, we can define three potential solutions, concerning the future of the mobility system in cities: technological solution for greening automobiles; shared mobility (carsharing, carpooling); integrated Mobility as a Service System (MAAS). These three solutions are not separated. Servitisation (expanding the range of services and proposing complex solutions) along the shared and integrated mobility roads can create stimuli for ever faster technological renovation of the automobile fleet.
5. In Bulgaria, work is under way to create conditions and develop capacity for using electrically-driven vehicles as alternative to the IC engine-driven ones, including hydrogen-driven ones. There is a national programme for research in the field of low carbon energy for transport. The high achievements under this programme, as well as the achievements of the student teams in the field of energy efficiency of electrically—and hydrogen fuel cell—powered vehicles are an attestation of the appropriate capacity building qualities.
6. The research done for the energy consumption of a river vessel, powered by solar panel energy allows to predict the hydrogen consumption for its propulsion and to build a river vessel powered by hydrogen fuel cell. The research on an electrically powered vessel with a mass of 1.5 t showed that the energy consumption is an average of about 102.49 kWh/100 km when sailing upstream and 32 kWh/100 km when sailing downstream at a speed between 7.8 and 10 km/h.
7. The implementation of multicriterial optimizing of public urban transport travel allows the use of two or more criteria for planning the public urban transport travels. Identifying Pareto-optimal discrete solutions allows the decision-maker to choose one of them.

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Environment Safety Improving Due to Railway Noise Management Decreasing of RMR Method Adaptation

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Abstract World Health Organization, as well as number of scientists and doctors indicate in their works that during last few decades, the noise has a significant impact on the environment, especially noise from quickly developing transportation systems [1, 2]. Environment noise pollution is being aligned in the same row with the air, water and soil pollution. In EU member states, the EC recommended interim method is being used (RMR, Reken—en Meetvoorschrift Railverkeerslawaai) [3]. It is obvious that RMR modelling method has certain applicability limitations, especially taking into account it's empirical character. If differences of local railway system are not taken into account correctly, the modelled noise levels can be significantly underpredicted. The monograph's objective is to qualitatively evaluate the applicability of RMR method, to adopt it to Latvian Railway conditions [4, 5], to elaborate guidelines for simplified adaptation and to develop recommendations for RMR method improvement.

Keywords RMR method · Railway noise · Trains · Sound pressure level

1 RMR Method Description

The RMR method provides two calculation procedures: the simplified for a total equivalent A-weighted noise level and a more detailed for noise level estimation in eight octave bands. The octave band method was the result of development, published in 2002, of the original version of the RMR method published in 1996 and is related

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to as SRMII, but the common RMR abbreviation is used within this report. Last update of the RMR method was in 2009, when the 11-th train type category was added to the previously described. Let us consider the RMR octave band method in more detail.

There are three train type categories currently in operation on Latvian railway, which correspond to those described in RMR: electric passenger trains—RMR category 1, diesel passenger trains—RMR category 6 and freight trains—RMR category 4, therefore the description of calculation method will be limited to these three categories.

For these three train categories 2 source heights are defined in RMR: L_{bs}—at the level of the railhead representing the track radiated noise and L_{as}—0.5 m above the railhead representing the wheel rolling noise.

The basic formula for the calculation of radiated sound power level, dB(A), by non-braking (index nr) trains of category c in the octave band i for the period of one hour is given by [3]:

$$E_{nr,i,c} = a_{i,c} + b_{i,c}\lg\left(\frac{v_{nr}}{v_0}\right) + 10\lg\left(\frac{Q_{nr}}{Q_0}\right) + C_{bb,m,i}, \tag{1}$$

where

$a_{i,c}$ and $b_{i,c}$	radiation indexes defined for each train category c and each octave band i from Table 1;
v_{nr}	average train speed, km/h;
v_0	normalizing value, 1 km/h;
Q_{nr}	traffic intensity, i.e. number of trains per hour, h^{-1};
Q_0	normalizing value, 1 h^{-1};
$C_{bb,m,i}$	track correction for track type bb from Table 2 and rail disconnection class m from Table 3 [3].

The same calculation is performed for braking trains (index r) [3]:

$$E_{r,i,c} = a_{i,c} + b_{i,c}\lg\left(\frac{v_r}{v_0}\right) + 10\lg\left(\frac{Q_r}{Q_0}\right) + C_{bb,m,i}, \tag{2}$$

and the braking noise is accounted as [3]:

$$E_{brake,i,c} = a_{i,c} + b_{i,c}\lg\left(\frac{v_r}{v_0}\right) + 10\lg\left(\frac{Q_r}{Q_0}\right) + C_{brake,i,c}. \tag{3}$$

where

$C_{brake,i,c}$	correction for braking noise for train category c in octave band i from Table 5.

For diesel passenger trains additional correction for engine noise can be applied in the same form for both non-braking and braking trains [3]:

Table 1 Radiation indexes a and b for three train categories in eight octave bands

Train category c	Radiation index	Octave band centre frequency, Hz and number i							
		63	125	250	500	1000	2000	4000	8000
		1	2	3	4	5	6	7	8
1	a	20	55	86	86	46	33	40	29
	b	19	8	0	3	26	32	25	24
4	a	30	74	91	72	49	36	52	52
	b	15	0	0	12	25	31	20	13
6	a, v < 60	54	50	66	86	68	68	45	39
	b, v < 60	0	10	10	0	10	10	20	20
	a, v ≥ 60	36	15	66	68	51	51	27	21
	b, v ≥ 60	10	30	10	10	20	20	30	30
6 engine	a, v < 60	72	88	85	51	62	54	25	15
	b, v < 60	−10	−10	0	20	10	20	30	30
	a, v ≥ 60	72	35	50	68	9	71	1	−3
	b, v ≥ 60	−10	20	20	10	40	10	40	40

Table 2 Correction coefficients $C_{bb,i}$ as a function of track type bb and octave band i

Octave band i	$C_{bb,i}$							
	bb = 1	bb = 2	bb = 3	bb = 4	bb = 5	bb = 6	bb = 7	bb = 8
1	0	1	1	6	6	–	6	5
2	0	1	3	8	8	–	1	4
3	0	1	3	7	8	–	0	3
4	0	5	7	10	9	–	0	6
5	0	2	4	8	2	–	0	2
6	0	1	2	5	1	–	0	1
7	0	1	3	4	1	–	0	0
8	0	1	4	0	1	–	0	0

Table 3 Rail disconnection class m description

Description	m class	f_m
Track with rail joints	2	1/30
1 switch	2	1/30
2 switches per 100 m	3	6/100
More than 2 switches per 100 m	4	8/100

$$E_{engine,i,c} = a_{engine,i,c} + b_{engine,i,c} \lg\left(\frac{v}{v_0}\right) + 10 \lg\left(\frac{Q}{Q_0}\right). \tag{4}$$

In case of rail disconnection class m = 1 (jointless rails), the correction coefficient $C_{bb,i,m}$ is taken from Table 2. For other disconnection classes, Table 4, the correction coefficient $C_{bb,i,m}$ is given by [3] (Table 5):

$$C_{bb,i,m} = C_{3,i} + 10 \lg(1 + f_m A_i), \tag{5}$$

where

$C_{3,i}$ correction values from Table 2 for bb = 3;
f_m is taken from Table 3;
A_i is taken from Table 4.

Table 4 Correction factor A_i as a function of octave band i

Octave band i	A_i
1	3
2	40
3	20
4	3
5, 6, 7, 8	0

Table 5 Correction factor A_i as a function of octave band i

Octave band i	$C_{brake,i,c}$	
	c = 1, 4	c = 6
1	−20	−20
2	−20	−20
3	−20	−20
4	−2	−20
5	2	−20
6	3	−20
7	8	−20
8	9	−20

The rolling noise is highly dependent on the roughness profiles of rails and wheels. In RMR method the average national wheel and rail roughness for Dutch railway networks is already included in correction coefficients $C_{bb,i,m}$. In case of rails with joints, the roughness is less important, because the rolling noise radiation will be dominated by impact noise from joints, however in case of jointless rails (m = 1), the rolling noise levels can vary significantly due to differences between local and national average rail and wheel roughness profiles. Therefore for jointless rails $C_{bb,i}$ could be modified by [3]:

$$C_{c,bb,i} = C_{c,bb,i} - \left(L_{i,rtr,ni}(\lambda_i) \oplus L_{i,rveh,ni,c}(\lambda_i)\right) + \left(L_{i,rtr,loc}(\lambda_i) \oplus L_{i,rveh,loc,c}(\lambda_i)\right), \tag{6}$$

where

$C_{bb,i}$	is taken from Table 2; $L_{i,rtr,ni}(\lambda_i)$ and $L_{i,rtr,loc}(\lambda_i)$—correspondingly average national and local rail roughness, dB_{mkm};
$L_{i,rveh,ni,c}(\lambda_i)$ and $L_{i,rveh,loc,c}(\lambda_i)$	correspondingly average national and local wheel roughness for train category c, dB_{mkm};
λ_i	roughness wavelength, m;
$\oplus$	energetic summation operation.

The roughness profile can be measured using different direct and indirect measurement technics.

For electric and diesel passenger trains the noise radiation at the source heights L^{bs} and L^{as} is given by [3]:

$$E_{bs,nr,i,c} = E_{nr,i,c} - 1 \tag{7}$$

$$E_{bs,r,i,c} = E_{r,i,c} - 1 \tag{8}$$

$$E_{as,nr,i,s} = E_{nr,i,c} - 7 \tag{9}$$

$$E_{as,r,i,c} = E_{r,i,c} - 7 \tag{10}$$

For freight trains the noise radiation at the source heights L^{bs} and L^{as} is given by [3]:

$$E_{bs,nr,i,c} = E_{nr,i,c} - 3 \tag{11}$$

$$E_{bs,r,i,c} = E_{r,i,c} - 3 \tag{12}$$

$$E_{as,nr,i,c} = E_{nr,i,c} - 3 \tag{13}$$

$$E_{as,r,i,c} = E_{r,i,c} - 3 \tag{14}$$

The correction constants show that for Dutch railway network track is the dominant rolling noise source in case of electric and passenger trains. In case of freight trains wheels and track contributions to rolling noise assumed to be equal.

The radiated sound power level, dB(A), by non-braking and braking trains of n categories present at the source heights Lbs and Las in octave band i for the period of one hour is calculated by [3]:

$$L_{E,i}^{bs} = 10\lg\left(\sum_{c=1}^{n} 10^{E_{bs,nr,i,c}/10} + 10^{E_{bs,r,i,c}/10}\right), \tag{15}$$

$$L_{E,i}^{as} = 10\lg\left(\sum_{c=1}^{n} 10^{\frac{E_{as,nr,i,c}}{10}} + 10^{\frac{E_{as,r,i,c}}{10}} + 10^{\frac{E_{brake,i,c}}{10}} + 10^{\frac{E_{engine,nr,i,c} \oplus E_{engine,r,i,c}}{10}}\right). \tag{16}$$

It can be seen from (16) that in the RMR the engine and braking noise source height is defined at 0.5 m above railhead.

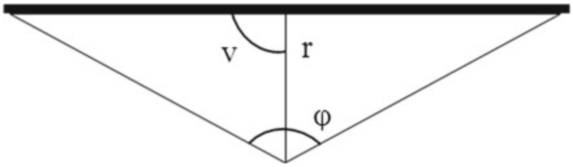
The A-weighted sound pressure spectrum in the point of reception is found by calculation of sound pressure level in each octave band i due to source n using [3]:

$$\Delta L_{eq,i,n} = L_{E,n} + L_{GU} - L_{OD} - L_{SW} - L_R - 58.6, \tag{17}$$

where

$\Delta L_{eq,i,n}$	sound pressure level in the point of reception, dB(A);
$L_{E,n,i}$	radiated sound power level due to source n in octave band i (15, 16), dB(A);
LGU	attenuation due to distance, dB;
LOD	attenuation due to propagation, dB;
LSW	screening effect if present, dB;
LR	reflection effect if present, dB.

Fig. 1 Angles φ, v and measurement distance r



The constant value of 58.6 accounts for various corrections such as reference values and the conversion of sound power to sound pressure containing distance and surface quantities.

The equivalent A-weighted sound pressure level (dB(A)) in the point of reception is calculated energetically summating pressures due to all sources N in all octave bands i [3]:

$$L_{Aeq} = 10\lg\sum_{n=1}^{N}\sum_{i=1}^{8}10^{\Delta L_{eq,i,n}/10}, \tag{18}$$

$$L_{GU} = 10\lg\left(\frac{\varphi}{\varphi_0}\frac{r_0}{r}\sin v\right), \tag{19}$$

where

φ and v angles shown in Fig. 1;
φ_0 normalizing value, 1°;
r distance from track centre line to receiver point, m;
r_0 normalizing value, 1 m.

Attenuation due to propagation is given by [3]:

$$L_{OD} = D_L + D_B + C_M, \tag{20}$$

where

DL attenuation due to air absorption, dB;
DB attenuation due to ground effect, dB;
CM meteorological correction factor, dB.

$$D_L = r\delta_{air}, \tag{21}$$

where δ_{air}—air absorption coefficient in accordance to ISO 9613-2 [6, 7].

$$C_M = C_0\left(1 - 10\frac{h_h+h_w}{r_0}\right) \text{for}\, r_0 > 10(h_h + h_w)$$
$$C_M = 0\, \text{for}\, r_0 \le 10(h_h + h_w). \tag{22}$$

where

h_h source height above the average terrain level in the source area, m;
h_w height of the point of reception above the average terrain level in the assessment area, m;
r_0 horizontally measured distance between source and the point of reception, m;
C_0 constant which depends on the local meteorological statistics for wind speed and direction and temperature gradients, typical value is in the range from 0 to 5 dB.

When determining the attenuation due to ground effect dB, the horizontally measured distance between the source and the point of reception is divided into three areas: source area, middle area and assessment area. The source area has a length of 15 m and the assessment area a length of 70 m. The remaining section of the distance r_0 between the source and the assessment point forms the middle area. If the distance between the source and the point of reception is less than 85 m, the length of the middle area is zero.

If the distance r_0 is less than 70 m, the length of the assessment area is equal the distance r_0.

If the distance r_0 is less than 15 m, both the length of the source area and the assessment area is equal the distance r_0.

The ground absorption factor is calculated for all three areas. The absorption contribution corresponds to the ratio of the section length of the area concerned, if it is not acoustically hard, divided by the total length of the area concerned. If the length of the middle area is zero, the absorption contribution is one.

To calculate the ground attenuation the following factors are taken into account: r_0, h_h, h_w, B_b—ground absorption factor in the source area, B_m—round absorption factor in the middle area, B_w—ground absorption factor in the assessment area, S_w—effectiveness of ground attenuation inside the assessment area, S_b—effectiveness of ground attenuation inside the source area.

If h_h is less than zero, the value zero is given to h_h and the same applies for h_w.

The ground attenuation is calculated using equations listed in Table 6 [3]:

The functions $\gamma(x, y)$ in Table 6 are determined using (23–36) [3].

$$\gamma_0(x, y) = 1 - 30\frac{x}{y} \quad \text{for } y \ge 30x$$
$$\gamma_0(x, y) = 0 \quad \text{for } y < 30x \tag{23}$$

$$\gamma_2(x, y) = 3\left(1 - e^{\frac{-y}{50}}\right)e^{-0.012(x-5)^2} + 5.7\left(1 - e^{-2.8\times10^{-6}y^2}\right)e^{-0.09x^2} \tag{24}$$

$$\gamma_3(x, y) = 8.6\left(1 - e^{\frac{-y}{50}}\right)e^{-0.09x^2} \tag{25}$$

Table 6 Determination of ground absorption as a function of the octave band i

i	Ground attenuation (dB)			
1		$-3\gamma_0(h_h + h_w, r_0)$		−6
2	$\left[(S_h\gamma_2(h_h, r_0) + 1)B_b\right]$	$-3(1 - B_m)\gamma_0(h_h + h_w, r_0)$	$\left[(S_w\gamma_2(h_h, r_0) + 1)B_w\right]$	−2
3	$\left[(S_h\gamma_3(h_h, r_0) + 1)B_b\right]$	$-3(1 - B_m)\gamma_0(h_h + h_w, r_0)$	$\left[(S_w\gamma_3(h_h, r_0) + 1)B_w\right]$	−2
4	$\left[(S_h\gamma_4(h_h, r_0) + 1)B_b\right]$	$-3(1 - B_m)\gamma_0(h_h + h_w, r_0)$	$\left[(S_w\gamma_4(h_h, r_0) + 1)B_w\right]$	−2
5	$\left[(S_h\gamma_5(h_h, r_0) + 1)B_b\right]$	$-3(1 - B_m)\gamma_0(h_h + h_w, r_0)$	$\left[(S_w\gamma_5(h_h, r_0) + 1)B_w\right]$	−2
6	B_b	$-3(1 - B_m)\gamma_0(h_h + h_w, r_0)$	$+B_w$	−2
7	B_b	$-3(1 - B_m)\gamma_0(h_h + h_w, r_0)$	$+B_w$	−2
8	B_b	$-3(1 - B_m)\gamma_0(h_h + h_w, r_0)$	$+B_w$	−2

$$\gamma_4(x, y) = 14\left(1 - e^{\frac{-y}{50}}\right)e^{-0.46x^2} \tag{26}$$

$$\gamma_4(x, y) = 5\left(1 - e^{\frac{-y}{50}}\right)e^{-0.9x^2} \tag{27}$$

If there is no barrier between source and the point of reception, both S_w and S_h are given value of 1. In case of barrier presence, the S_w is found using (29) and S_h using (30).

If there are objects on the way from source to receiver which interfere with the sound transmission, the screening effect LSW is taken into account. The formula for calculating the attenuation by an object of variable shape contains two factors. The first factor describes the screening by an equivalent idealized barrier (a thin, vertical plane). The height of the equivalent barrier corresponds to the height of the obstructing object. The upper edge of the barrier corresponds to the highest edge of the obstacle.

The second factor is important only if the object profile deviates from that of the idealized barrier. The profile is defined as the cross-section of the sector plane of the attenuating object. The attenuation of the object is equal to the attenuation of the equivalent barrier minus a correction factor C_p depending on the profile. If several attenuating objects are present in a sector, only the object that in the absence of the others would cause the most attenuation is taken into account.

The equations given hereafter are valid for barrier heights up to 4.0 m, placed not closer than 4.5 m from the centre of the track. For other cases the screening effect can be overestimated.

The idealized barrier between source and point of signal reception is shown in Fig. 2.

In order to calculate attenuation due to an object, the following parameters are taken into account: r_0, m; r_w, m; r—distance between the source and point of reception along the shortest connection line, m; h_h, m; h_w, m; z_h—source height above railhead, m; z_w—reception point height above railhead, m; h_T—height of the upper edge of the idealized barrier relative to the average level in 5.0 m range around the barrier; object profile.

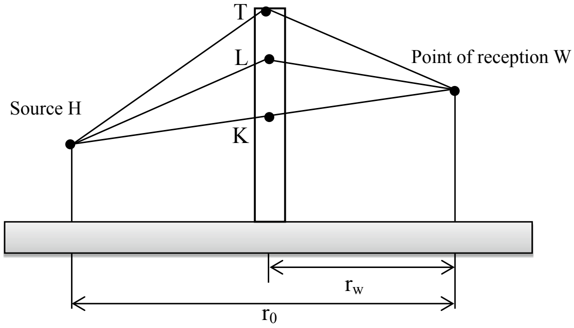


Fig. 2 The idealized barrier between source and point of signal reception

In Fig. 2 K represents intersection point of the barrier and the line of sight between source and receiver; L represents intersection point of the barrier and a curved sound ray, that reaches the assessment point from the source point in downwind conditions and T represents the upper edge of the barrier.

If the T, L and K point heights above railhead are Z_T, Z_L and Z_K correspondingly, then the distance between points K and L, m is calculated as follows [3]:

$$Z_L - Z_k = \frac{r_w(r_0 - r_w)}{26r_0}, \tag{28}$$

$$S_w = 1 - \frac{r_0 - r_w}{r_0}\frac{3h_e}{3h_e + h_w + 1} \quad \text{for } h_e > 0, \tag{29}$$

$$S_h = 1 - \frac{r_w}{r_0}\frac{3h_e}{3h_e + h_h + 1} \quad \text{for } h_e > 0, \tag{30}$$

where

$h_e = Z_T - Z_L$ the effective barrier height, m.

The attenuation factor LSW is calculated using [3]:

$$L_{SW} = HF\left(N_f\right) - C_p, \tag{31}$$

where

$H = 0.25h_T 2^{i-1}$	screening performance factor and i—octave band number;
C_p	correction factor depending on the object profile, listed in 1. attachment, dB;
$F(N_f)$	function from Fresnel number N_f, defined in Table 7.

The Fresnel number is determined as [3]:

$$N_f = 0.37\varepsilon 2^{i-1}, \tag{32}$$

where

Table 7 Definition of function $F(N_f)$

N_f interval		$F(N_f)$
From	To	
$-\infty$	-0.314	0
-0.314	-0.0016	$-3.682 - 9.288\log_{10}\lvert N_f\rvert - 4.482\log_{10}^2\lvert N_f\rvert - -1.170\log_{10}^3\lvert N_f\rvert - 0.128\log_{10}^4\lvert N_f\rvert$
-0.0016	0.0016	5
0.0016	1.0	$12.909 + 7.945\log_{10} N_f + 2.612\log_{10}^2 N_f + 0.073\log_{10}^3 N_f - -0.184\log_{10}^4 N_f - 0.032\log_{10}^5 N_f$
1.0	16.1845	$12.909 + 10\log_{10} N_f$
16.1845	$+\infty$	25

ε acoustic pathway, m.

$$\begin{aligned} \varepsilon &= (HT + TL) - (HL + LW) \quad \text{for} \quad Z_T \geq Z_K, \\ \varepsilon &= 2r - (HT + TL) - (HL + LW) \quad \text{for} \quad Z_T < Z_K. \end{aligned} \tag{33}$$

The reflection effect LR takes into account the loss of sound energy of the sound ray propagating from source to receiver and is calculated using [3]:

$$L_R = N_{ref}\delta_{ref}, \tag{34}$$

where

N_{ref} the number of reflections;
δ_{ref} reflection loss, dB.

$$\delta_{ref} = 10\log_{10}(p), \tag{35}$$

where

$p = 1$ is reflection coefficient and α is absorption coefficient.

The recommended value of δ_{ref} for buildings is 0.8 and 1.0 dB for all other objects, unless the object is proven to be sound absorbing.

Summary

To estimate the sound pressure level in the point of reception due to known source radiation it is necessary to take into account many aspects of sound wave propagation in the media. Railway noise propagation is influenced by ground effects, atmospheric absorption, wind and temperature gradients, obstacles (reflective or absorptive) and foliage in the propagation path, etc. Moreover, the situation is complicated by the movement of the source (train).

Various analytical models with certain limitations can be used to describe sound propagation under different conditions and with relatively high level of accuracy, however they are often demanding for large computational resources. The analytical models of railway noise propagation are mainly used for reference calculations in relatively simple conditions.

For practical applications such as noise map development, the approximated and statistically averaged semiempirical and empirical models of railway noise radiation and propagation are used.

RMR method allows to calculate the noise spectrum in eight octave bands from passing trains in the point of reception and in general form can be expressed as a function of many parameters:

$$L_i = Y\{[T, V/V_0, Q, Q_0, B_r, E_n, A_e, T_r, D, R_r, W_r], GU, OD, SW, R\}, \quad (36)$$

where

L_i	A-weighted sound pressure level in the point of reception in octave band i, dB(A);
T	train type;
V/V_0 and Q/Q_0	are correspondingly normalized train speed and traffic intensity;
B_r	braking noise;
E_n	engine noise;
A_e	aerodynamic noise;
T_r	track type;
D	rail disconnection class;
R_r and W_r	rail and wheel roughness;
GU	attenuation due to distance;
OD	attenuation due to propagation;
SW	screening effects;
R	reflection effects.

Parameters in square brackets define the train pass-by noise radiation spectrum, while other parameters account for noise propagation from source to receiver. Due to empirical nature of the RMR method, it is obvious that the applicability of the method in other from Dutch national railway conditions should be evaluated and in case of necessity the new radiation parameters have to be defined.

In case of Latvian railway, there are few foreseen technical differences, compared to standard European rail system, which likely lead to differences in radiated noise levels (Figs. 3 and 4):

Fig. 3 The standard European rail system. Track width—1435 mm, wheel diameter—920 mm, cylindrical wheels

Fig. 4 The standard Latvian rail system. Track width—1520 mm, wheel diameter—920 1220 mm, conical wheels, differences in braking systems

2 Measurement Description

RMR method description [3] contains three methods for adaptation to local railway conditions:

- A—simplified method to assign new vehicle to existing category;
- B—method to define a new rail vehicle category;
- C—method to define new track type.

The easiest and fastest way is to assign existing train types to the already defined in RMR method, based on propulsion type, vehicle type, brake system type, etc. However, this can only be done if it was proved that pass-by noise levels are similar to those of Dutch trains. In order to verify that, simplified single channel measurements of equivalent pass-by noise levels (spectra) can be done. If the pass-by noise spectra levels in all octave bands found to be lower compared to those modelled by RMR method, train type can be assigned to the existing category.

Measurements of pass-by noise spectrums of all train types operating on Latvian railway were performed. Of the most importance was the investigation of rolling noise for all train types on railway track with jointless rails, however, the traction noise, braking noise and impact noise was also additionally examined. It was discovered, that in case of all train types operating on Latvian Railway, actual pass-by noise levels are higher compared to those modelled by RMR method. Measurement results are summarized in next section.

Since it was not possible to assign any of the operated on Latvian Railway train types to the defined in RMR train type categories, additional measurements were performed following method B. A dedicated measurement and measurement result post-processing system was developed based on data acquisition hardware and software from Labview, providing useful practical tool for RMR method adaptation.

No new track types were defined using method C within the framework of this project.

Following sections provide description of measurement conditions, measurement system and setup and measurement results.

2.1 Measurement Conditions

In accordance with ISO 3095 [8] and RMR methods measurement recommendations, the measurement site was selected to offer free field conditions. The soil was free of obstacles and there were no reflecting objects such as walls, buildings, slopes or bridges closer than 3 times the distance between source and receiver. The ground was relatively flat and within a level from 0 to (-1) m relative to the top of the rail. The soil was free of strongly absorbing surfaces such as snow, high grass, or strongly reflecting surfaces such as water.

The measurement place was selected at the railway line Riga—Aizkraukle, near the train station Dole and in accordance with above requirements. The only notable

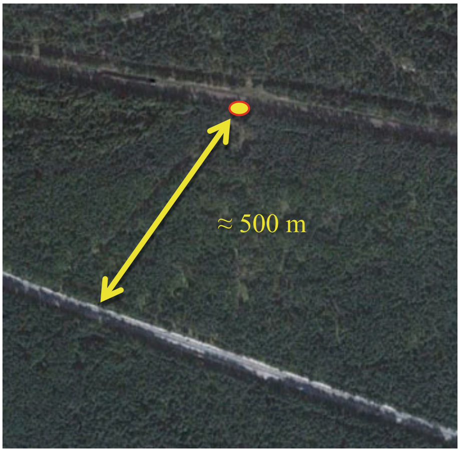


Fig. 5 Measurement place

background noise source was the traffic noise from the road at the distance of about 500 m from the railway line. Though, the railway line is separated from the road with the forest and the monitored background noise levels at the measurement place were constantly well below the railway noise levels and did not affect measurements.

To minimize meteorological effects during measurements, the measurements were performed when wind speed at the microphone height was less than 5 m/s and there was no falling rain or snow (Figs. 5 and 6).

2.2 Measurement System and Setup

2.2.1 A—Simplified Method Measurements

For A—simplified method measurements, in accordance with RMR recommendations and ISO 3095, single channel sound spectra analyser was used for pass-by noise octave band spectra measurements, meeting the requirement for class 1 measurement equipment specified in IEC 61672 and IEC 61260.

The microphone position was at the distance of 7.5 m from the track centre and at the height of 1.2 m above the railhead (Fig. 7).

Calibration of the whole measurement chain was performed before and after each measurement session to make sure that difference between two adjacent calibration factors does not exceed the value of 0.5 dB (Fig. 8).

For train pass-by noise measurements, the measurement time interval T was chosen, so the measurement starts when the A-weighted sound pressure level is 10 dB lower than found when the front of the train is opposite the microphone position. The measurement is stopped when the A-weighted sound pressure level is 10 dB lower than found when the rear of the train is opposite the microphone position, Fig. 9.

Fig. 6 Measurement place

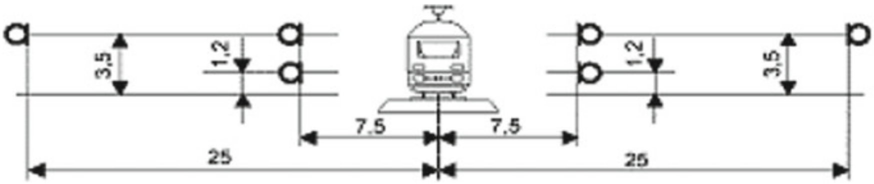


Fig. 7 Microphone position at the test site, distances and heights are in meters

2.2.2 B—Method Measurements

Considerable effort has been spent at a European level to establish comprehensive methods for the experimental assessment of rolling noise emission of rail-bound vehicles and tracks. Big part of work was concentrated in the European METARAIL and STAIRRS projects. The objective of these was to improve the accuracy and the reproducibility of pass-by noise measurements compared to the standards that were current at that time. A further aim was to develop experimental methods separately to identify the contributions to rolling noise of the vehicles and the tracks [9].

In these projects, measurement methods were developed that could determine the combined wheel/rail roughness and the 'transfer functions' for the vehicle and the track, that is, the separate noise contributions per unit roughness. The roughness and

Fig. 8 Microphone position at measurement site

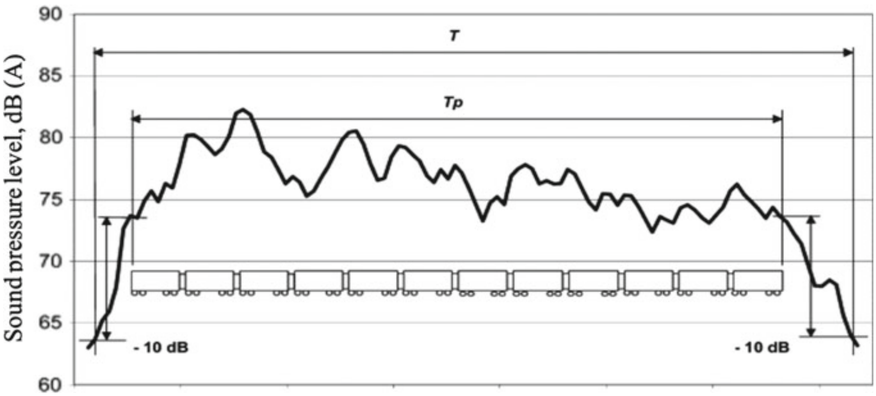


Fig. 9 Measurement time

Table 8 Several levels of railway noise characterization

	Obtained quantities			Applications and notes
	Total	Vehicle	Track	
Level 0 (no separation)	L_{ptot}			Overall levels, large spread
Level 1 (sound separation)	L_{ptot}		L_{ptr}	For assessing track or vehicle noise control measures
Level 2 (sound and roughness separation)	L_{ptot}	L_{rveh}, L_{Hreh}, $Lpveh$	L_{rtr}, L_{Htr}, L_{ptr}	For independent characterization of tracks and vehicle
Level 3 (sound roughness and dynamics separation)	L_{ptot}	L_{rveh}, L_{Hreh}, L_{pveh} mobilities and others	$L_{r\text{tr}}$, $L_{H\text{tr}}$, $L_{p\text{tr}}$, mobilities and others	Partly using calculation, when vehicle not available

transfer function spectra provide a powerful basis by which vehicles and tracks can be characterized by measurement, to a high extent, independent of the running speed and site conditions. Such a description of the track and rolling stock allows the prediction of rolling noise spectra for different combinations of vehicles and track from those at which the characteristics have been measured. The measurement effort is limited; only straightforward one-third octave band measurements of pass-by sound pressure and vertical railhead vibration are needed [10].

Within the framework of this project different rolling noise source separation techniques were analysed, but the pass-by method published by Jansens et al. [11] was chosen as the most straightforward and technically less demanding. Moreover, this method was already applied by number of other researchers showing accurate and reproducible results. Description of the method presented below is taken from [11–14].

Levels of Rolling Noise Source Separation

Jansens et al. [11] describes four different levels of railway noise characterization: (Table 8)

At "level 0" no noise source separation is possible. This actually represents the A—simplified method for train type assignment to existing in RMR method categories.

At "level 1" pass-by noise is separated into the part radiated by the vehicle and the part radiated by the track. Several such methods have been presented, such as microphone array methods [11, 15, 16] or other techniques [17, 18]. Within their range of validity, these methods provide the possibility to separate noise radiated by the vehicle and that from the track. This allows a clearer test and quantification of the effect of noise control measures. The descriptors at this level are: total pass-by sound

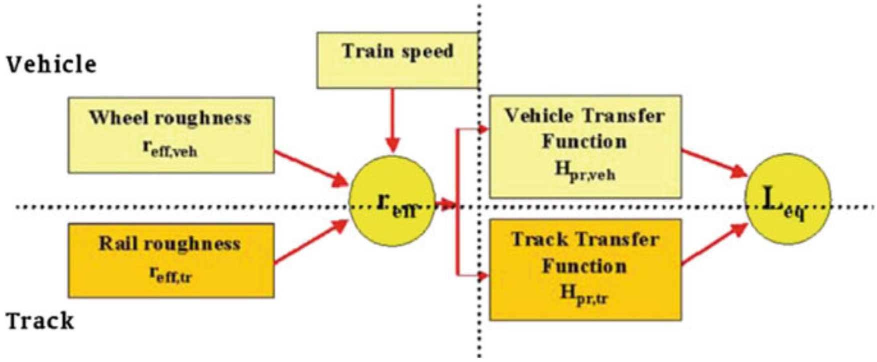


Fig. 10 Measurement quantities for rolling noise, separated into excitation and transfer functions and vehicle and track components

pressure level, and sound pressure level of the vehicle and sound pressure level of the track.

However, it does not allow determination (prediction) of noise radiation from any train on any track. For example, the sound radiated by a vehicle on a particular track does not uniquely characterize that vehicle, since the track roughness has a direct influence.

Therefore, a further level of detail, "level 2", is defined. A method at this level, aims not only to separate the total sound level during a train pass-by into a vehicle part and a track part, but also to provide the wheel and track roughness. The quantities to be measured now are: total pass-by sound pressure level, and sound pressure level of the vehicle, sound pressure level of the track, wheel and track roughness spectra (as a function of wavelength).

Considering that the sound pressure level of a vehicle will vary from track to track due to roughness level variation, it is now possible to derive the ratio of sound pressure to roughness amplitudes. It can be anticipated, based on TWINS [9, 10] theory, that this ratio is, to a good approximation, invariant from site to site [19].

Finally, besides the vehicle and track roughness, it is also known from rolling noise theory, that the dynamics of vehicle and track can also influence one another significantly. This could be expressed at a "level 3" of detail. A measurement method at this level of detail must, in addition to the noise and roughness levels, provide data on wheel, track and contact spring dynamics [20]. However, for the range of common track and wheel types it can be expected that the influence of different dynamic characteristics can be neglected [21]. Only in cases that involve very small wheels, resilient wheels or exotic rail types, is a significant effect on the noise expressed as a dB level to be expected. Therefore, the aim of this project was noise detailing of "level 2".

In order to handle data of pass-by measurements at the level 2 detail, some conventions and definitions are needed. Figure 10 presents quantities that provide a simple breakdown of pass-by noise into quantities determined by the wheel and the track.

Wheel roughness, rail roughness and train speed characterize the excitation of rolling noise at the wheel–rail contact. The ratios of the resulting trackside wheel and track noise components to the roughness excitation are expressed as transfer functions. The transfer function captures every aspect of sound transmission of the vehicle (or track) implicitly: the wheel vibration response to the excitation, its radiation, and the sound transmission to the trackside [8].

The transfer functions are normalized to the number of axles per unit length and the roughness is 'filtered' by the wheel/rail contact filter (CF).

Wheel and Rail Roughness

The wheel and rail roughness amplitude levels, $L_{r,w}(\lambda)$ and $L_{r,r}(\lambda)$, are expressed as one–third octave band spectra with respect to wavelength λ. The dB reference is 1 μm rms amplitude. The one-third octave band centre values are taken to be in the series 1.0; 1.25; 1.6; 2.0; 2.5; 3.15; 4.0; 5.0; 6.3; 8.0; 10 cm and so on.

In the current method, the so-called effective roughness is used. This is the roughness spectrum as if the total contact patch was represented by a single point; which means that the effective roughness already includes the averaging and 'filtering' effects of the wheel/rail contact patch. The 'filter' (contact filter, CF) expresses the way in which wavelengths of roughness shorter than the length of the contact patch (in the direction of travel and perpendicular to it) are averaged and thus reduced in effect [22].

The combined roughness of wheel and rail follows from:

$$L_{r,tot}(\lambda) = L_{r,w}(\lambda) \oplus L_{r,r}(\lambda) = 10lg\left\{10^{\left(\frac{L_{r,w}(\lambda)}{10}\right)} + 10^{\left(\frac{L_{r,r}(\lambda)}{10}\right)}\right\}, \tag{37}$$

where the operator ⊕ is used to signify the energy sum.

This definition of the roughness spectrum differs a little from roughness data that is obtained using a sharply pointed sensor. The result using such a sensor does not account for the contact filter effect.

Nevertheless, using an appropriate contact filter function CF(λ) [23, 24], this 'direct' roughness data can be converted into the effective roughness. The effective rail roughness $L_{r,r}(\lambda)$ relates to the rail roughness measured using direct surface scanning $L_{r,r,dir}(\lambda)$ as

$$L_{r,r}(\lambda) = L_{r,r,dir}(\lambda) + CF(\lambda). \tag{38}$$

A similar expression holds for wheel roughness. The contact filter CF(λ) depends somewhat on the wheel load, the wheel diameter, the wheel profile and the rail profile.

Transfer Functions

The ratio of radiated noise and roughness for both vehicle and track are expressed as transfer functions $L_{H,veh}$ and $L_{H,tr}$:

$$L_{H,tr}(f_{to}) \equiv L_{p,tr}(V, f_{to}) - 10lg\left(\frac{N_{axle}}{L_{wagon}}\right) - L_{r,tot}(\lambda(V, f_{to})), \quad (39)$$

$$L_{H,veh}(f_{to}) \equiv L_{p,veh}(V, f_{to}) - 10lg\left(\frac{N_{axle}}{L_{wagon}}\right) - L_{r,tot}(\lambda(V, f_{to})), \quad (40)$$

where f_{to} is the one-third octave band centre frequency;

$L_{p,tr}(V, f_{to})$ is the measured equivalent continuous sound pressure level from the track at pass-by speed V taken over the time interval for the vehicle to pass the measurement location "from buffer to buffer";

$L_{p,veh}(V, f_{to})$ is the equivalent continuous sound pressure level for the vehicle;

N_{axle} is the number of axles per wagon;

L_{wagon} is the wagon length, (m).

Since the roughness is a function of a single wheel–rail contact but the sound levels depend on the spacing of the axles, the vehicle and track transfer functions must be normalized for the axle density N_{axle}/L_{wagon}.

The transfer function may be described as the sound pressure level at the track-side corresponding to one axle per metre length of the vehicle, due to a combined roughness amplitude of 1 μm [25].

Although not directly obvious from (39) and (40), rolling noise theory shows that the effects of rolling on the frequency content of the spectrum are small enough for the transfer functions to be assumed not to depend on train speed. The change in sound pressure level with the train speed is caused by the frequency shift of the roughness spectrum only. This holds as long as linear theory applies (not where wheel flats or severe rail surface defects exist), and no sound sources other than rolling noise are significant in the measured sound pressure signal [26].

Trackside Total Sound Pressure

Using the definitions of the previous sections, the trackside vehicle sound pressure can be reconstructed as:

$$L_{p,veh}(V, f_{to}) = L_{H,veh}(f_{to}) + 10lg\left(\frac{N_{axle}}{L_{wagon}}\right) + L_{r,tot}(\lambda(V, f_{to})), \quad (41)$$

and a similar expression exists for the track noise $L_{p,tr}(f)$.

The total sound level due to rolling noise is the energy sum of vehicle and track noise:

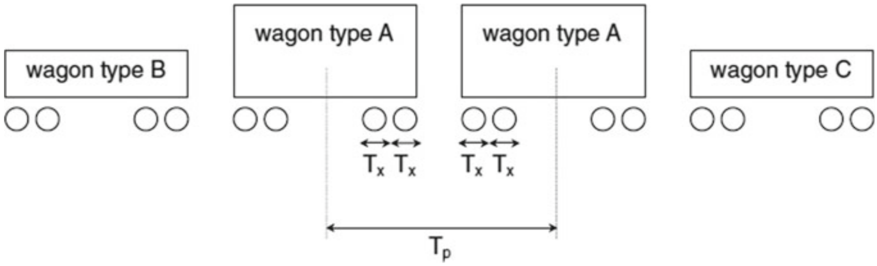


Fig. 11 Time intervals T_x and T_p for combined roughness and spatial decay rate definition

$$L_{p,tot}(V, f) = L_{p,veh}(V, f) \oplus L_{p,tr}(V, f), \tag{42}$$

where $L_{r,tot}(f_{to})$ is the one-third octave band level of combined effective roughness of wheel and rail and.

$L_{a,meas}(f_{to})$ is the one-third octave band level of measured equivalent vertical rail acceleration, averaged over the wheel passage time interval T_x.

$A_1(f_{to})$ Is the Level Difference Between the Average Vibration at the Measurement Position (for Determination of Combined Roughness)

The combined effective roughness of wheel and the rail is derived directly from the measurement of vertical rail vibrations. The one-third octave band levels $L_{a,meas}(f_{to})$ of the average acceleration over the wheel passage interval Tx is determined, see Fig. 11. This interval is taken as the time for the wheel to travel a short distance e.g. 1.8 m; the moment the wheel passes the accelerometer is taken as the centre of this interval. The combined roughness is defined as:

$$L_{r,tot} = L_{a,meas}(f_{to}) - A_1(f_{to}) - A_2(f_{to}) - A_4(f_{to}) - 40lg(2\pi f_{to}), \tag{43}$$

example, underneath the rail) and the rail head,

$$A_1(f_{to}) = L_{a,meas}(f_{to}) - L_{a,head}(f_{to}). \tag{44}$$

$A_2(f_{to})$ is the level difference between the vibration displacement at the contact point on the rail head and the combined effective roughness $L_{r,tot}(f_{to})$:

$$A_2(f_{to}) = L_{x,contact}(f_{to}) - L_{r,tot}(f_{to}). \tag{45}$$

$A_4(f_{to})$ is the level difference between the vibration at the contact point and the average vibration over the wheel passage interval T_x:

$$A_4(f_{to}) = L_{a,head}(f_{to}) - L_{a,contact}(f_{to}). \tag{46}$$

The term 40 $lg(2pf_{to})$ converts from acceleration $L_{a,contact}(f_{to})$ to displacement $L_{x,contact}(f_{to})$.

Conversion spectrum A_1

The accelerometer will be not be located on the rail head, but at a different part of the rail cross-section.

$A_1(f_{to})$ converts the measured acceleration $L_{a,meas}(f_{to})$ to the vertical acceleration of the rail head $L_{a,head}(f_{to})$,accounting for the cross-sectional deformation of the rail. In [27] it is shown, that $A_1(f_{to}) \approx 0$ up to 4 kHz for an accelerometer underneath the centre of the rail foot in the vertical direction.

Conversion spectrum A_2

The level difference $A_2(f_{to})$ between the vibration displacement at the contact point $L_{x,contact}(f_{to})$ on the railhead and the combined effective roughness $L_{r,comb}(f_{to})$, which describes to which extent roughness induces rail vibration, is the result of the wheel rail interaction. As shown in [24],

$$A_2 = 20lg\left(\frac{|\alpha_R|}{|\alpha_R + \alpha_W + \alpha_C|}\right), \tag{47}$$

where α_R is the rail point receptance at the contact;

α_W is the wheel point receptance at the contact;

α_C is the receptance of the contact stiffness.

A study [23, 24] using the TWINS model, shows that the spectrum A_2 in fact does depend slightly on the track properties. The pad stiffness is shown to be the most influential parameter. The spectrum of A_2 is listed in Table 9 for the 63–5000 Hz one-third octave frequency bands for different ranges of pad stiffness. The ranges of pad stiffnesses are given in Table 10. These values of A_2 are determined to within a variation of ±3 dB in individual one-third octave bands for a range of conventional wheels. This uncertainty is transferred to the result for the combined roughness. Since this does not lead to greater uncertainties than those found unconventional roughness measurements, it is acceptable. Averaging over more measurements with different train speeds further diminish this distribution since peaks and dips in the frequency spectrum A_2 average out.

Conversion spectra A_4

The level difference $A_4(f_{to})$ between the vibration at the contact point $L_{a,contact}(f_{to})$ and the average vibration over the wheel passage interval $L_{a,head}(f_{to})$ depends on the track decay rate, i.e. the spatial vibration decay D along the track, which is expressed in dB/m [9, 27]:

$$A_4(f_{t0}) \approx \frac{D}{2.75} \tag{48}$$

The vibration decay D from Eq. (48) can be derived from hammer impact measurement (usually an unloaded track) or from the pass-by measurements themselves by

Table 9 Spectra A_2 (f_{to}) for three categories of rail pad stiffness [24]

Frequency (Hz)	Soft pad	Medium pad	Si iff pad
63	1.0	−3.0	−3.0
80	4.1	2.3	2.3
100	2.7	2.6	2.6
125	0.9	0.8	0.8
160	0.1	0.0	0.0
200	0.0	0.0	0.0
250	−0.6	0.0	0.2
315	−1.2	−2.6	−0.1
400	−1.3	−3.9	−2.8
500	−0.9	−4.8	−6.5
630	−0.9	−3.2	−8.1
800	−1.6	−2.6	−6.9
1000	−2.7	−4.3	−5.0
1250	−5.6	−6.2	−4,4
1600	−8.0	−7.5	−6.4
2000	−9.5	−8.8	−8.4
2500	−10.0	−9.8	−9.5
3150	−11.3	−11.2	−11.1
4000	−13.7	−13.6	−13.6
5000	−14.9	−14.8	−14.8

Table 10 Ranges of pad stiffness applying to different categories of pads used in defining standard spectra for A_2 [24]

	Soft pad	Medium pad	Stiff pad
Bibloc sleeper	≤400 MN/m	400-800 MN/m	≥800 MN/m
Monobloc sleepers	≤800 MN/m	≥800 MN/m	–
Wooden sleepers	All	–	–

evaluating the vibration decay around a wheel. This latter approach has the advantage of determining the decay with the presence of the pre-load of the train.

The decay D is derived from the evaluation of the ratio of the integrated vibration level over a length L_2 versus the integrated vibration over a short length L_1 directly around the wheels. L_2 is taken as a relatively long length, e.g. the whole train pass-by, a group of wagons, or a vehicle length. The corresponding time interval is T_p, Fig. 2.7. L_1 is taken as 1.8 m, from—0.9 m to +0.9 m around each wheel position, corresponding to the time interval T_x in Fig. 2.7. The wheel position is determined by a wheel-position trigger signal in the measurements.

$$D(f) = -\frac{20}{L1} * lg(1 - R(f)), \tag{49}$$

where vibration ratio R(f) is:

$$R(f) = \frac{A\frac{2}{\sum L_1}}{A\frac{2}{\sum L_2}}. \tag{50}$$

The quantities $A^2_{\Sigma L_1}$ and $A^2_{\Sigma L_2}$ can be determined straightforwardly from measured acceleration signals as integrated squared vibration in one-third octave bands.

Combined Transfer Function Measurement

From a single train pass-by, the combined effective roughness can be determined. The combined transfer function is found by subtracting this roughness from the measured sound level:

$$L_{H,tot} = L_{p,tot} - 10lg\left(\frac{N}{L}\right) - L_{r,tot} \tag{51}$$

The basic measurement set-up consists of one microphone and one accelerometer, Fig. 2.8. The microphone position is 7.5 m from the track centre and 1.2 m above rail head. To avoid interference from accompanying wheel types, at least two vehicles of one type are required, Fig. 2.7. The equivalent sound pressure level $L_{p,tot}(f_{to})$ is measured by taking the average sound pressure level over interval T_p. The vertical rail acceleration is measured underneath the centre of the rail foot. The rail acceleration $L_{a,meas}(f_{to})$ should be averaged over T_x to obtain $L_{r,tot}(V/f_{to})$.

Vibration over two rails can vary, as well as sound radiation levels. If the vibration levels vary more than 3 dB for two rails, it is recommended to average results between two rails. It is also essential not to have more than 3 dB difference in noise radiation on both sides from the train [28]. To control that condition, it is preferable to have measurement setup with 2 accelerometers and 2 microphones. To decrease potential error due to local conditions of the selected measurement place, it is preferable to make measurements at few rail cross sections.

To estimate the transfer function of the train or the track it is recommended to use reference track or reference train correspondingly. Reference train or track is selected to radiate as low noise as possible [29].

In ideal case, the reference train should radiate no sound, so that the track transfer function equals the measured combined transfer function (51) for a pass-by of that train:

$$L_{H,track} \equiv L_{H,tot}|_{ref.vehicle} = L_{p,tot} - 10lg\left(\frac{N}{L}\right) - L_{r,tot}|_{ref.vehicle}. \tag{52}$$

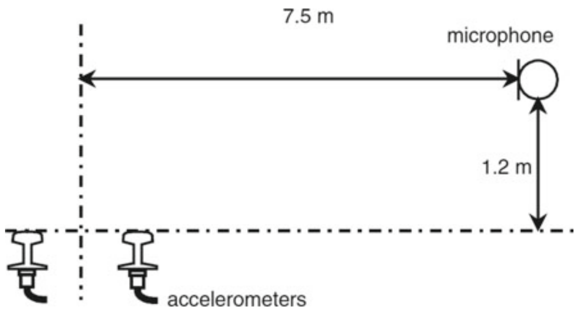


Fig. 12 Location of microphone and accelerometers

Of course, all vehicles will radiate sound, so a useful approximation of such a vehicle is sought. Similarly, the vehicle reference function could be determined using a "reference track", a track with very low noise radiation. Alternatively, the vehicle transfer function can be derived from the energy difference of the track transfer function and the total transfer function of a particular vehicle A:

$$L_{H,veh} = L_{H,tot}|_{vehA} \ominus L_{H,tot}|_{ref.vehicle}. \tag{53}$$

The method presented is valid under the following conditions. No sources other than rolling noise should be present (e.g. no aerodynamic effects at high-speed trains, no horns sounding, no train pass-bys on the adjacent tracks). Especially in the lower frequency range (below 100 Hz) and/or lower train speeds (below 40 km/h) care must be taken over traction noise. Braking of the train should be avoided during determination of the transfer functions to avoid braking noise. If the roughness of the two rails of the track differ greatly, the measured transfer function will not be representative, as the noise of the wheel and the rail on one side of the track will be predominant.

Measurement Procedure

In order to derive the transfer functions and roughness spectra of a vehicle and rail, the following steps are taken.

1. Instrument the track according to Fig. 12. In one measurement cross-section, one accelerometer and one microphone are used. Preferably, a trigger device is used to indicate the precise wheel passing times.
2. Measure pass-bys using the above set-up for the desired vehicles and speeds.
3. Measure some pass-bys using a 'reference' vehicle.
4. Measure the track roughness spectrum directly.
5. Determine the spatial decay using (49).
6. Determine combined roughness levels using (43).
7. Determine wheel roughness level.
8. Determine combined transfer function using (53).

9. Determine transfer function of the reference vehicle using (51) and (52).
10. Determine vehicle transfer function using (53).

Steps 5–10 can be performed at various speeds for various pass-bys. If more pass-bys at various train speeds are available, it is advisable to average the results.

Measurement System

In order to separate train and track rolling noise components following B—measurement method, integrated noise and vibration measurement system (further measurement system) was developed based on the data acquisition and postprocessing hardware and software from National Instruments:

– data acquisition system was developed as a fully automatic measurement, real-time computation and logging system.

Data acquisition system consists of the following equipment:

– NI 9184—4 slot synchronization chassis for National instruments measurement modules and PC connection establishment via Ethernet interface;
– NI 9234—4 channel ±5 V, IEPE and AC/DC Analog Input for microphone and accelerometer connection;
– NI 9411—6 channel ±5 to 24 V, Differential Digital Input for optical sensor connection used as a trigger for start/stop of the measurements;
– NI 9221—8 channel ±60 V Analogue input for second optical sensor connection used for wheel sensing at the measurement point.

Diffuse type optical sensors for measurement triggering, velocity calculation, wheelset counting and train type detection:

– Type 1 accelerometers and microphones with preamplifiers;
– PC, power supply.

Software has been designed in LabVIEW development system as LabVIEW VI (Virtual instrument).

Few software versions were prepared with two key functional differences: with and without real time data analysis. For all necessary data collection, it is enough to use version without real time analysis and then to use post analysis application. This allows so save machine time and secures more stable operation. Real time analysis was further development of the system in order to allow real time monitoring of the train pass-by noise and vibration, which can be used as an alarm system in case if any train or any dedicated wheelpair is causing too high noise or/and vibration levels. Such a system can be used for continuous monitoring and keeping noise levels under allowed limits as well as for train condition-based service planning.

Data acquisition system operates under following algorithm: measurement is triggered when the first wheelset crosses the first optical sensor (connected to NI module with digital inputs) and is stopped when the optical sensor has not been crossed by

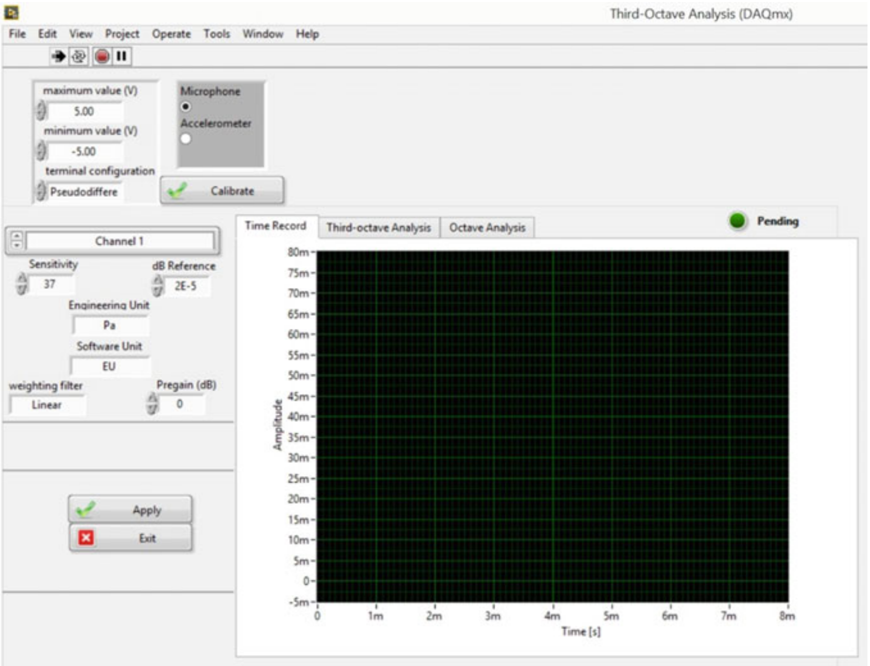


Fig. 13 Measurement system interface (data logging version)

the wheel for five seconds (may be adjusted). During the measurement, raw data from all sensors except the one optical used for triggering measurements is being logged. Raw data then either in real time either during postprocessing is used for all calculations. Such approach gives advantages over standardized measurement systems, where real-time processing is performed based on the presettings, so later postprocessing is usually limited. Using raw data in LabView, it is possible to perform all main analysis, including third octave band and octave band spectra analysis, FFT, weighting as well as transform raw data to wav file, perform different custom math calculations, build graphs, etc.

Main measurement system interface (data logging version) is shown in Fig. 13. It has basic start/stop functions only and calibration function to provide reliable measurement results. The graph shows measured raw data just for indicative purposes (to make sure that system is alive and operational).

In real time processing version, it is possible to see third octave band and octave band spectra of the noise and vibration signal, as well as indication of optical sensor signals and the train speed.

Main functional nodes of the system are presented in Fig. 14.

In order to double check the spectrum calculations and visualize measurement data in more convenient way, another LabVIEW virtual instrument was designed. Post processing allows user to view all the recorded data at once—WAV audio file, log

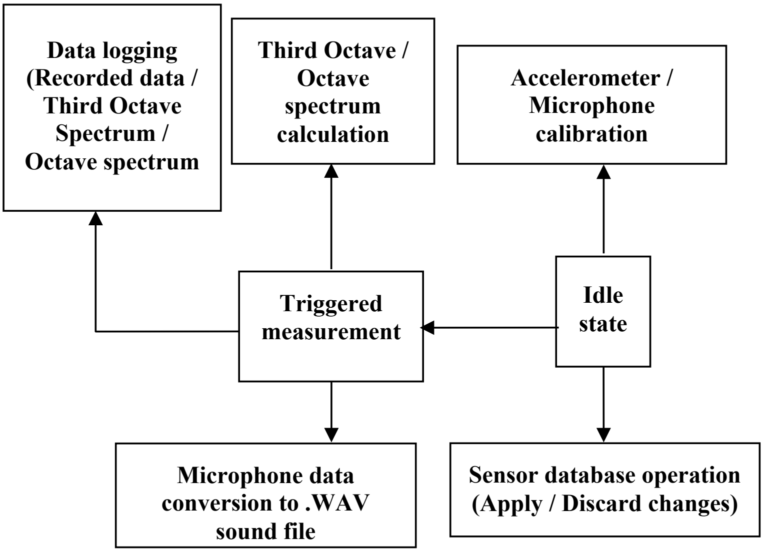


Fig. 14 Main functional nodes of the system

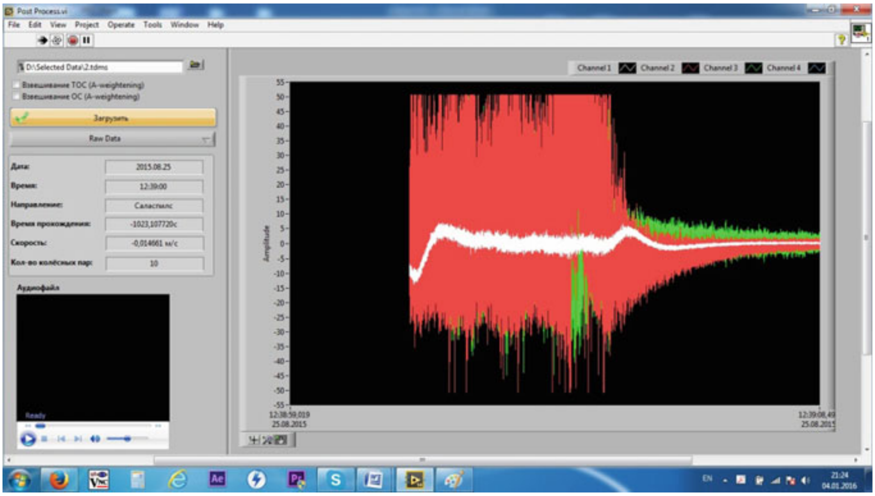


Fig. 15 Main screen of the post process

file, containing information about measurements, raw data, recorded from sensors, octave and third octave spectrums calculated during measurement as well as octave and third octave spectrums recalculated basing on the whole dataset with an option to apply A-weighting. Post processing virtual instrument windows are presented in Figs. 15, 16, 17, 18 and 19.

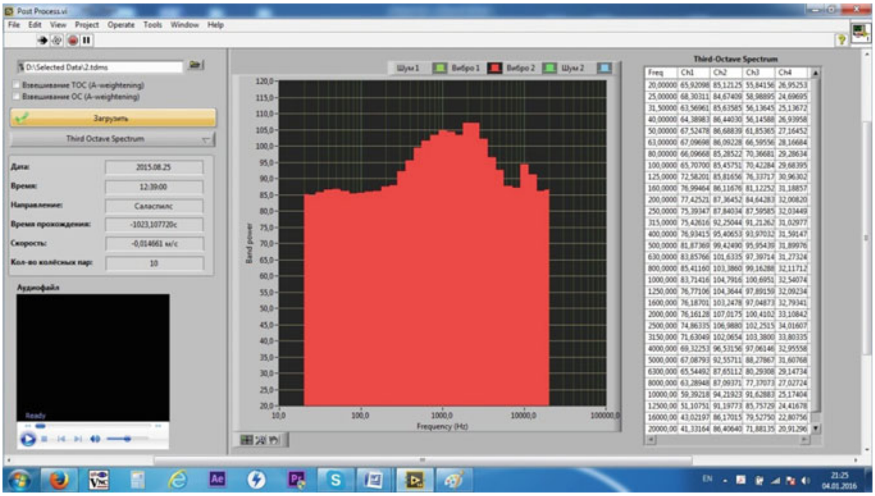


Fig. 16 Third octave spectrum screen of the post process

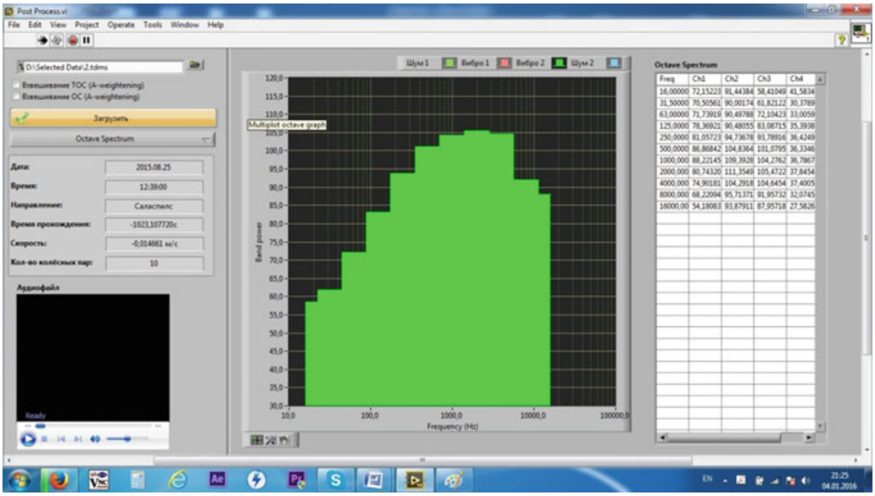


Fig. 17 Octave spectrum screen of the post process

Raw Data—the main screen, contains the time domain data, recorded with the corresponding sensitivity of the sensor;
Third Octave Spectrum—third octave spectrum calculated from the Raw Data dataset. Window contains a graph and a table with all the frequencies and their corresponding values;
Octave Spectrum—octave spectrum calculated from the Raw Data dataset. Window contains a graph and a table with all the frequencies and their corresponding values;

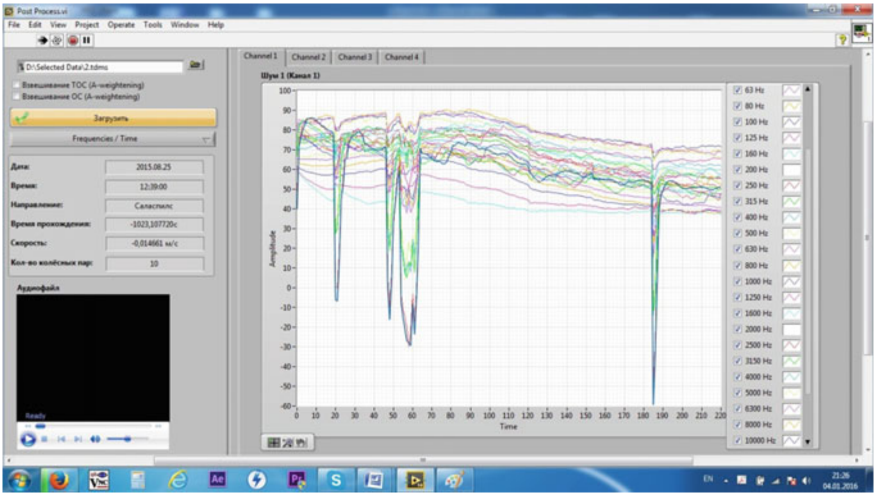


Fig. 18 Frequencies/time screen of the post process

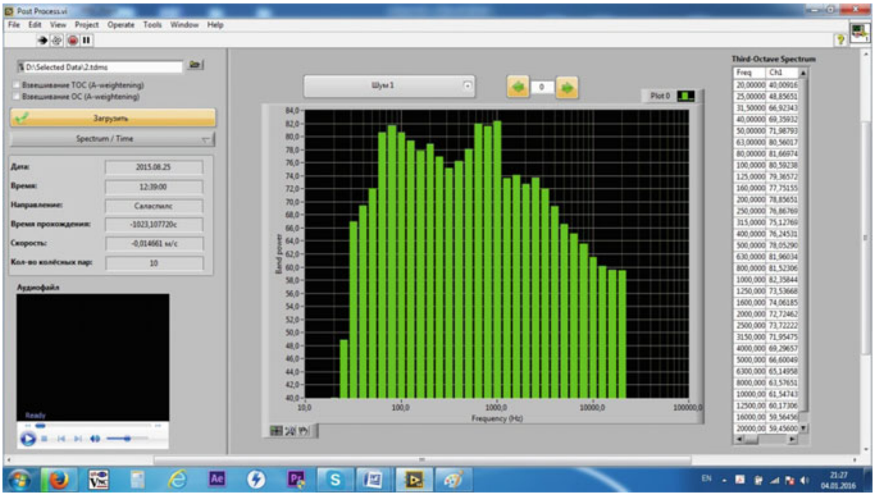


Fig. 19 Spectrum/time screen of the post process

Frequencies/Time—window contains change of amplitude of every frequency during the measurement, read from file. This window contains 4 tabs—one for each channel;
Spectrum/Time—window contains change of third octave spectrum during measurement, read from file. This window contains a menu for channel selection, “Back” and “Forward” buttons to navigate between the measurements and a numeric control to jump to a specific measurement.

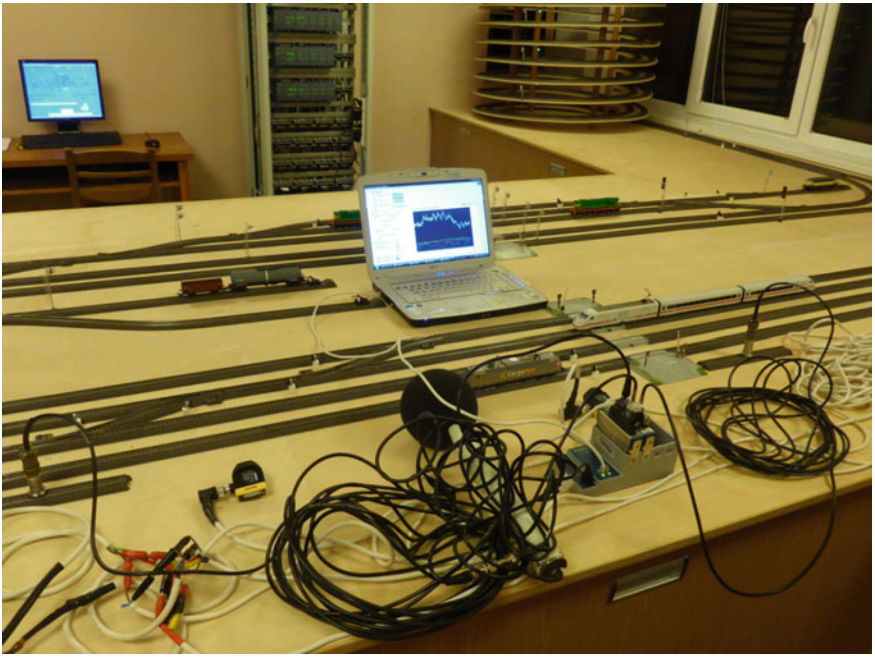


Fig. 20 Measurement system testing in laboratory

The VI also creates a new.tdms file in a root folder with following filename structure: "*originalfilename_EDITED.tdms*", where all the third octave spectrums are divided into separate tabs.

The measurement system was first tested in laboratory conditions (Fig. 20) however later it was modified and upgraded few times after testing in the field.

Installation of the measurement system in the field is shown in Figs. 21, 22, 23 and 24: vibration measurement of two rails of one track, sound measurements at both sides. Additionally, standardized sound meter for reference at one sound measurement point and two standardized sound meters close to the rail at different heights for traction noise source height estimation. By adding two more optical sensors to the measurement system it will be possible to perform measurements at both tracks simultaneously (one vibration and sound measurement point by track). NI data acquisition system offers modular design for cost effective system sizing and measurement system can be easily upgraded for simultaneous measurements at multiple tracks/rails/cross sections.

Fig. 21 Installation of optical diffuse sensor and accelerometer

Fig. 22 Installation of measurement system in the field

2.3 Rail Roughness Measurements

In order to qualitatively evaluate RMR method applicability and separate wheel and rail noise, direct rail rolling surface roughness measurements were performed. These were first measurements of this kind on Latvian railway.

Fig. 23 NI data acquisition hardware and power source in a case

Fig. 24 Ethernet connection allows for remote PC location

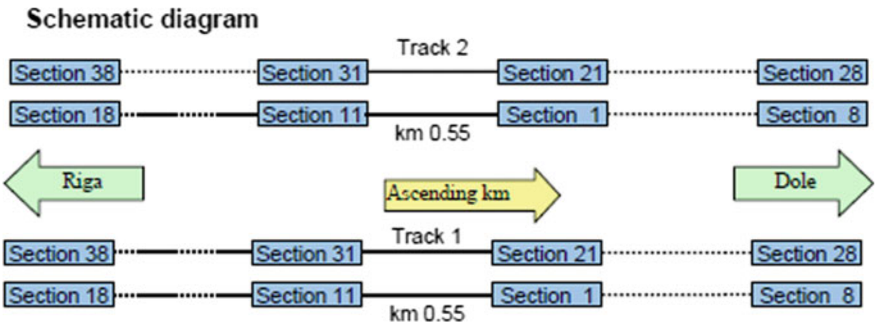


Fig. 25 Track status

2.3.1 Track Description

Place of measurement: track between "Dole" and "Salaspils" train stations.

Measured track: double line, straight section:

- track 1 from Riga to Salaspils, increasing kilometrage, both rails,
- track 2 from Salaspils to Riga, decreasing kilometrage, both rails.

Rails may have damage due to cargo trains with flat wheels.

2.3.2 Track Orientation and Measured Line Position

Measured area consisted from 16 linked measured sections with centre at km 0.55 for each rail. Each section was measured in the middle of rolling surface mirror. Joints (all joints were welded and visually hardly noticeable) were not excluded to obtain continual roughness diagram along whole testing area.

Repeatability test was made at section 21 at track 1.
Surface stability test was made at section 1 at track 2 (Fig. 25).

Rail head had clean surface. Corrosion of rail mirror was not visible. Track has welded joints. Track has local defects (Fig. 26).

2.3.3 Used Measuring Device

Laser roughness measuring device Salamander:
Producer: MEAS Prog. s.r.o.
Serial No: 130601-001-LMP01
Operator: Dr. Ing. Libor Veselý
Date of measurement: 4.10.2015–5.10.2015.

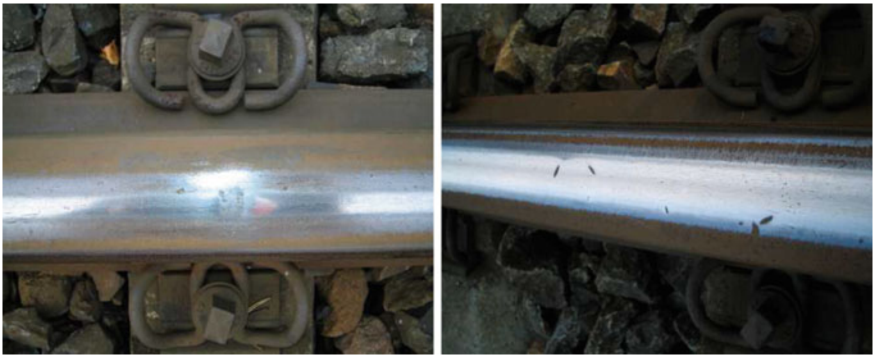


Fig. 26 Local rail surface defects

2.3.4 Description of Measuring Method

Each rail was divided to 16 linked sections with length over 10.3 m.

Roughness of each section was evaluated and spectra for each section were estimated.

Average roughness spectra for each rail were calculated.

Roughness for all rails was compared at on diagram.

One segment was measured 2 times and results compared for device repeatability test.

One segment was measured in the morning and in the evening and results compared for track surface stability test.

2.3.5 Measurement Repeatability Test

The repeatability test was made at section 21 at track 1 for the measuring device stability verification. The surface roughness was measured two times at the same place. Both measurements were evaluated, and result are shown in Fig. 27. The segment without local defects was chosen for the test.

2.3.6 Roughness Measurement Results

See Figures 28, 29, 30, 31, 32, 33, 34, 35 and 36; Table 11.

2.3.7 Conclusion of Rail Measurement

Test track measurement was made at both tracks and both rails at 16 approximately 10.3 m long segments for each rail.

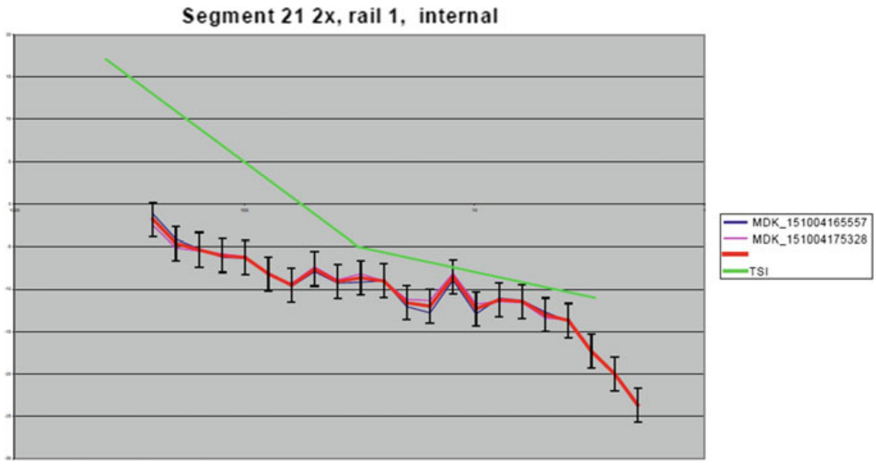


Fig. 27 Roughness measurement repeatability test result. Black lines on the diagram are ±2 dB tolerances, showing good repeatability in whole wavelength range

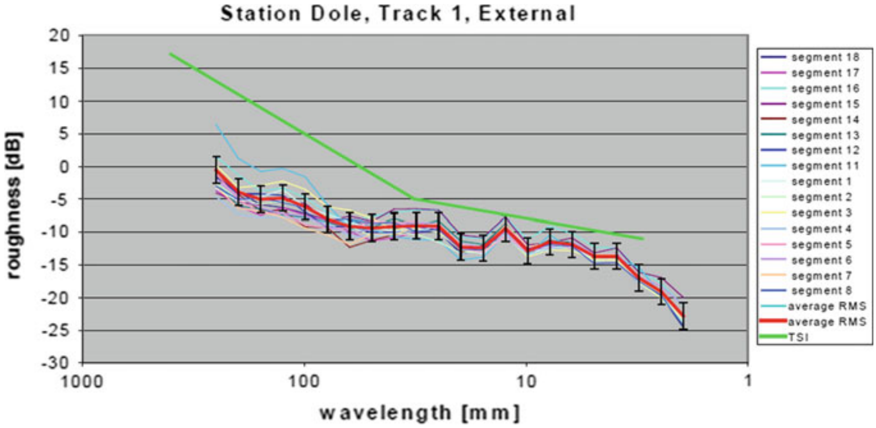


Fig. 28 Roughness measurement results. Track 1, external

Each rail sections were averaged separately and compared at one diagram.

Each rail was measured at constant line position in the middle of rail head surface "mirror".

All RMS average spectra of rails were compared at one diagram.

Average spectrum of all rails is under limit defined by EN15610. Only several individual segments and only in one third octave band were over TSI limit.

Roughness along the track is similar, therefore there was no need to measure rolling noise and vibration at multiple cross sections.

Both tracks are homogenous, local defects and joints do not generate extreme peaks. Stability of middle and longer wavelength of track is lower. It is probably due

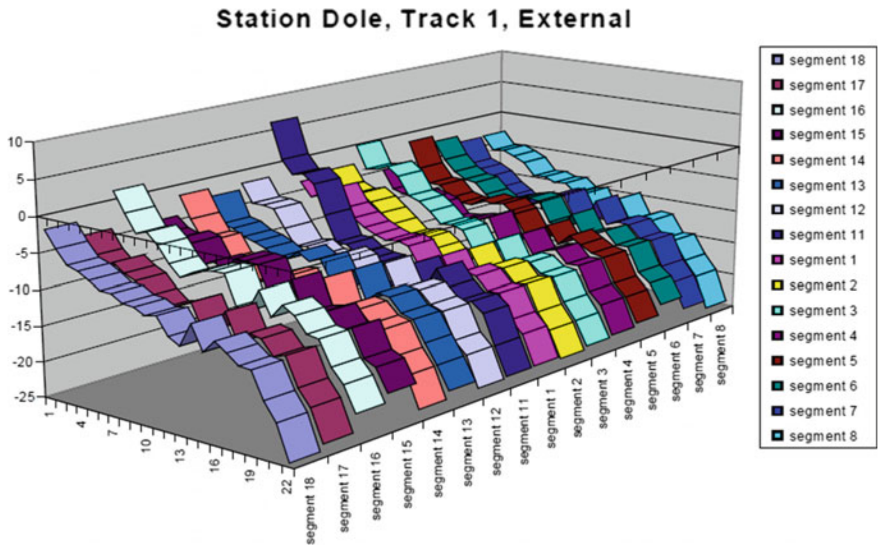


Fig. 29 Roughness measurement results. Track 1, external rail, spectra along the track

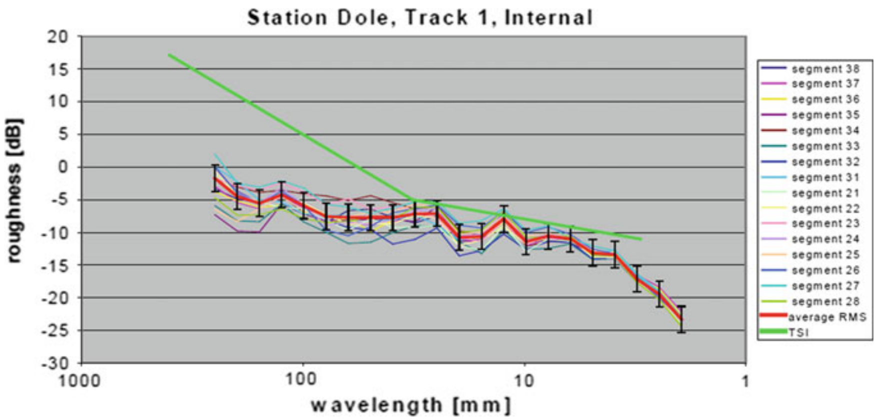


Fig. 30 Roughness measurement results. Track 1, internal rail, third octave band spectra

to passing heavy cargo wagons with flat wheels, which generate local micro-defects on the rail surface.

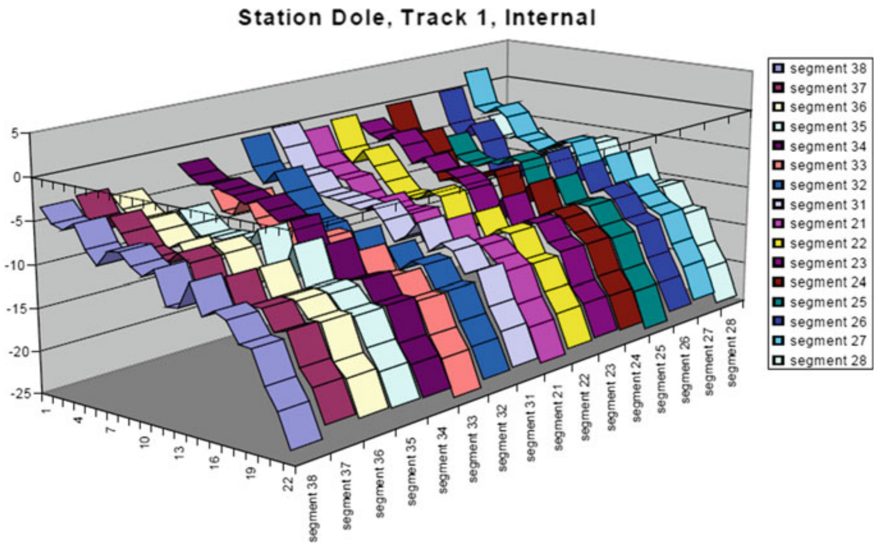


Fig. 31 Roughness measurement results. Track 1, internal rail, spectra along the track

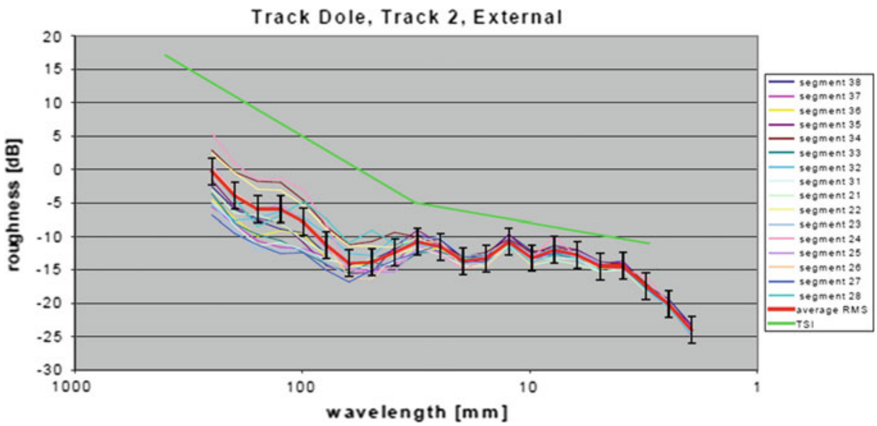


Fig. 32 Roughness measurement results. Track 2, external rail, third octave band spectra

3 Measurement Results

Since measurements were conducted in accordance with ISO 3095 and RMR recommendations, the A-weighted spectrums will be presented hereafter. The low frequency signals are highly attenuated, therefore only octave bands from 63 Hz to 16 kHz will be considered (the highest considered frequency in RMR is 8 kHz).

An interesting finding seen in Fig. 37 is that noise levels in 125 and 250 Hz octave bands are decreasing with increasing speed, this might be described by the

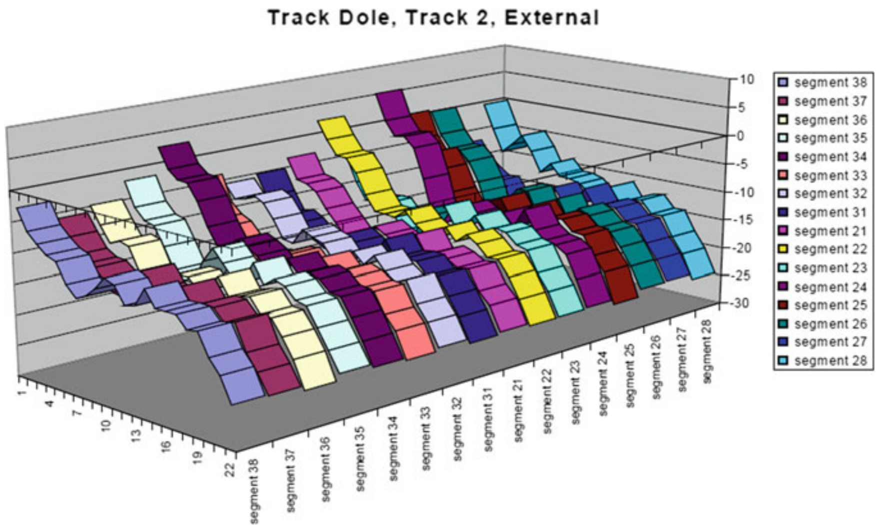


Fig. 33 Roughness measurement results. Track 2, external rail, spectra along the track

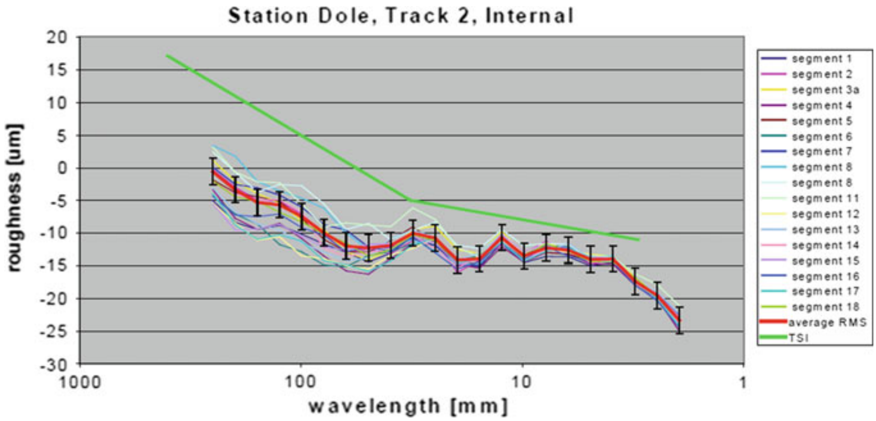


Fig. 34 Roughness measurement results. Track 2, internal rail, third octave band spectra

low frequency traction noise being louder during train acceleration or by differences between trains. In all other octave bands noise levels have increased with the speed.

In case of diesel passenger trains the noise levels in first three octave bands found to be speed independent at conventional speeds, but at speeds close to maximal the considerable increase at low frequencies occurs which might be due to exhaust and engine noise, Fig. 38. In other octave bands levels tend to increase with speed, lower levels at high frequencies for the fastest train might be due to differences between trains.

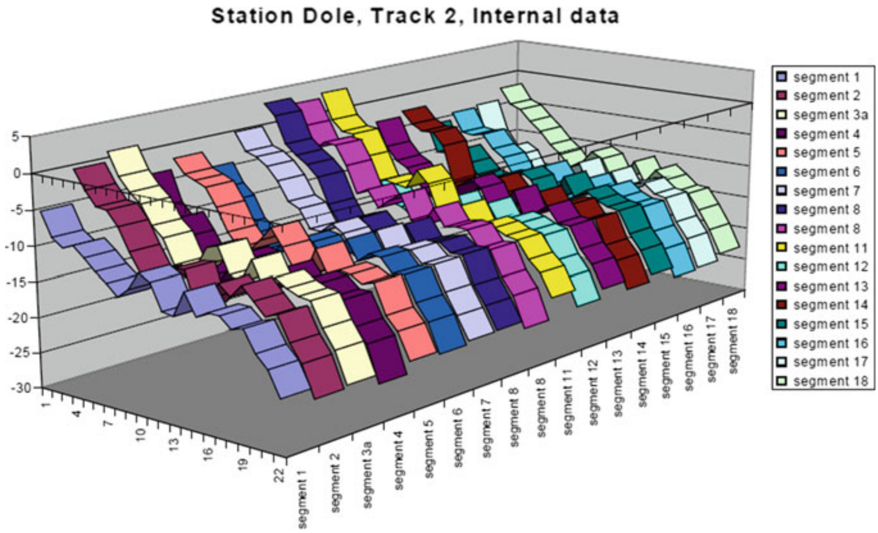


Fig. 35 Roughness measurement results. Track 2, internal rail, spectra along the track

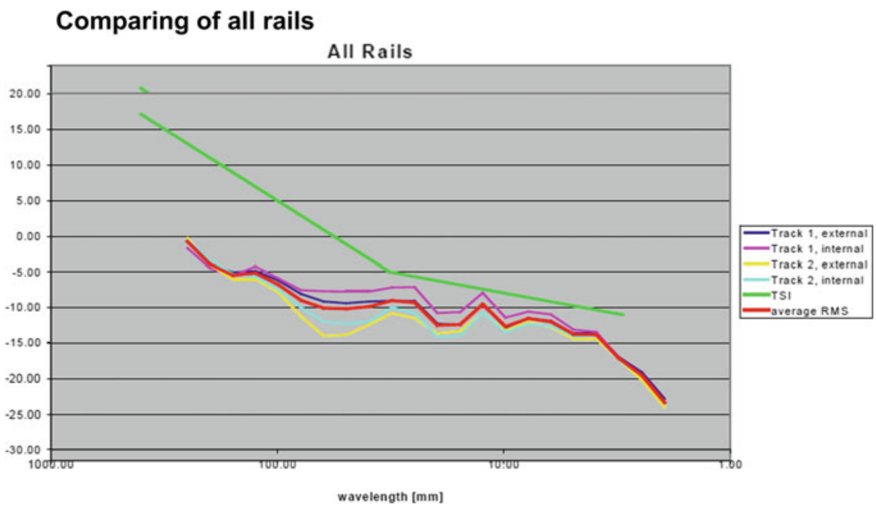


Fig. 36 Roughness measurement results. Comparison of all rails

The noise spectrum speed dependency of freight trains is shown on the example of mixed train (because of better available data for comparison) in Fig. 39.

Results for freight trains are hardly analysable due to possible differences between trains, however it can be clearly seen that the main increase in noise levels with increasing speed found in octave bands from 250 Hz to 4 kHz. Noise levels in 63 and 125 Hz octave bands are not speed dependent not taking into account data for the

Table 11 Roughness measurement results

Wavelength (mm)	Track 1, external	Track 1, internal	Track 2, external	Track 2, internal	Average RMS
250.00	−0.59	−1.70	−0.30	−0.59	−0.7637
198.43	−3.98	−4.49	4.00	−3.37	−3.9422
157.49	−5.07	−5.50	−5.98	−5.31	−5.4529
125.00	−4.88	−4.24	−5.98	−5.67	−5.1382
99.21	−6.17	−5.90	−7.83	−7.46	−6.764
78.75	−8.09	−7.54	−11.24	−9.96	−8.9647
62.50	−9.11	−7.70	−14.00	−11.97	−10.045
49.61	−9.36	−7.74	−13.83	−12.26	−10.164
39.37	−9.14	−7.73	−12.40	−11.91	−9.8648
31.25	−9.03	−7.16	−10.78	−10.00	−9.0232
24.80	−9.08	−7.11	−11.50	−10.75	−9.269
19.69	−12.26	−10.75	−13.63	−14.11	−12.483
15.62	−12.40	−10.63	−13.32	−13.95	−12.387
12.40	−9.43	−7.92	−10.76	−10.67	−9.5356
9.84	−12.83	−11.41	−13.22	−13.49	−12.658
7.81	−11.50	−10.58	−11.98	−12.26	−11.532
6.20	−11.87	−10.96	−12.74	−12.61	−11.985
4.92	−13.66	−13.09	−14.42	−14.03	−13.772
3.91	−13.68	−13.41	−14.40	−13.94	−13.842
3.10	−17.00	−17.14	−17.35	−17.35	−17.207
2.46	−19.08	−19.46	−20.13	−19.56	−19.539
1.95	−22.84	−23.33	−24.00	−23.34	−23.357

Final results table

slowest train (traction noise). At the high frequencies', levels tend to increase with speed, except the fastest train.

Spectrums of electric (red) and diesel trains (green) at speeds of 80 km/h and mixed freight train (black) at the speed of 70 km/h are combined in Fig. 40.

It can be seen that measured sound pressure levels in 4, 8 and 16 kHz are similar for diesel passenger and electric trains. Diesel trains radiate less noise in the middle frequency range, but have higher levels at low frequencies, Fig. 40. The mixed freight trains even at lower speed radiate higher noise levels at all frequency bands compared to other train types. The main part of low frequency radiation belongs to freight trains. This must be due to higher dynamic forces during freight train pass-by, causing increase in noise radiation by rails and sleepers. The freight train wheels also expected to be the roughest. No doubt that freight trains cause high level of the ground born vibrations which together with the radiated low frequency noise can propagate over long distances with a very little attenuation.

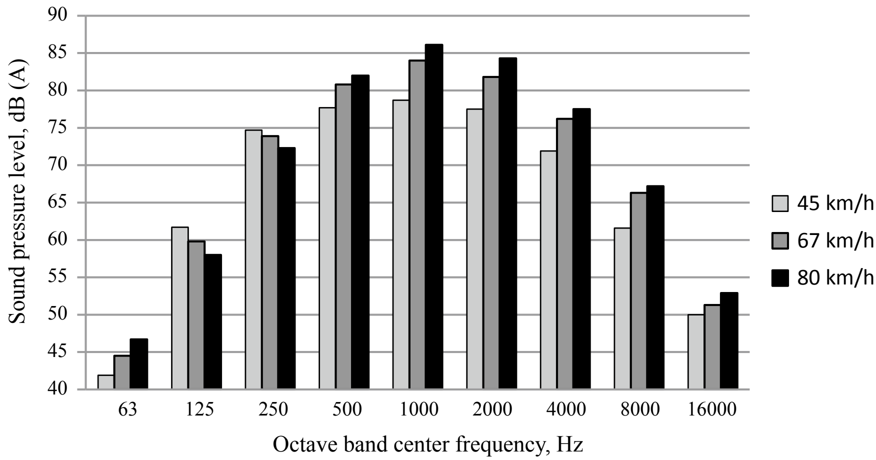


Fig. 37 Pass-by noise spectrums of electric trains at different speeds

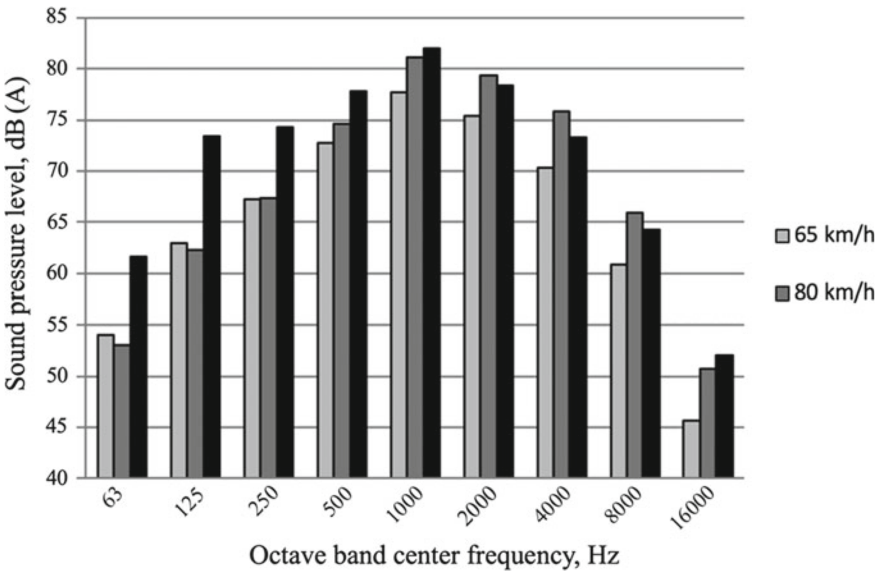


Fig. 38 Pass-by noise spectrums of diesel passenger trains at different speeds

It was discovered during current research that many of the empty freight trains radiated less noise, although it is hard to talk about the direct dependency of the radiation level on the train weight because of the low-correlated results. In Fig. 41 are shown pass-by noise spectrums of the same weight freight trains consisting from the same and only from wagons, travelling at the same speed of 70 km/h on the same track. The overall difference is about 7 dB(A). The same situation is with empty

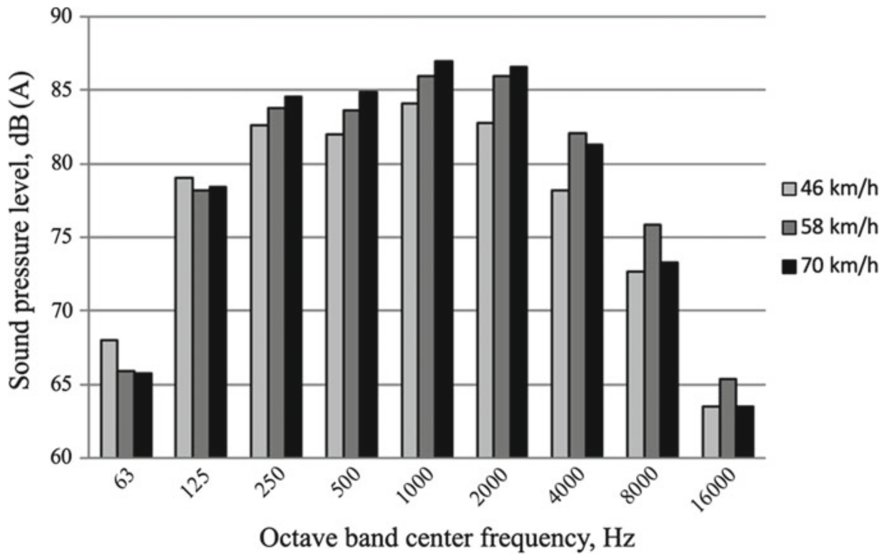


Fig. 39 Pass-by noise spectrums of freight mixed trains at different speeds

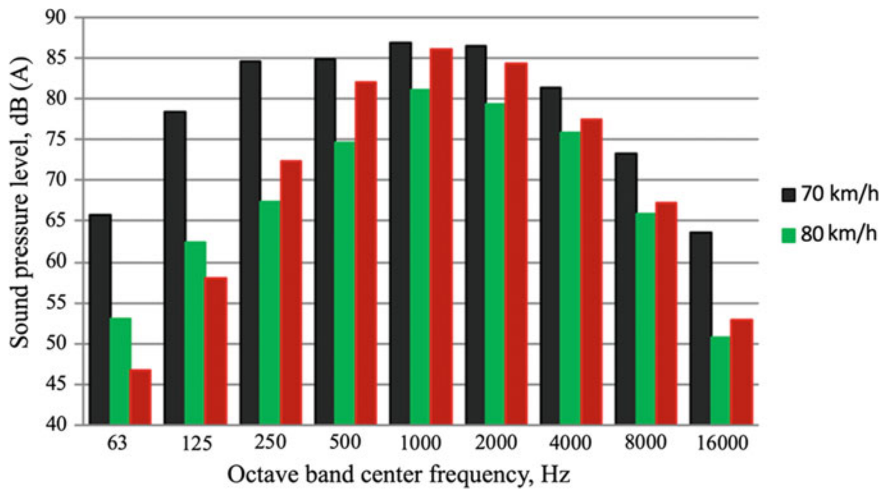


Fig. 40 Pass-by noise spectrums of different trains: black—freight train, green—diesel passenger train, red—electric train

trains, yet, it is hard to distinguish between the weight and wheel roughness effect on the noise radiation.

Let us consider the effects of traction and braking noise of trains on Latvian railway.

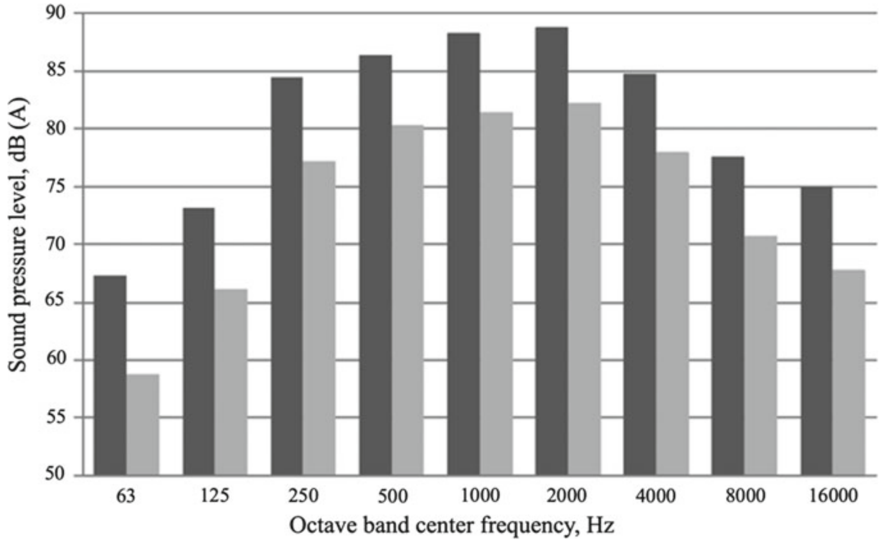


Fig. 41 Pass-by noise spectrums of freight trains

In Fig. 42 are shown sound pressure levels of diesel passenger train pass-by noise in low frequency bands and the total A-weighted levels. It can be seen that at the beginning of the measurement (left side) when the locomotive is opposite the microphone, the sound pressure levels in 31.5, 63, 125, 250 and 500 Hz octave bands are higher compared to other part of rolling stock (10 wagons, at the speed of 84 km/h).

Sound pressure levels in other frequency bands are similar for locomotive and rolling stock, Fig. 43.

The 1 kHz octave band is of the main interest with the highest noise levels. If we assume that for this frequency the main source are rails (Fig. 42), we know that for diesel and electric passenger trains the rail source reduction would have a noticeable effect on the total noise level, however, this would probably have only a partial effect in case of freight trains, where the noise peaks are found also in 2 kHz octave band.

In case of all freight trains the increased level of low frequency traction noise is seen in the 63 Hz octave band. No doubt, that the traction noise of freight locomotives is important also in adjacent octave bands, but it is masked by other sources and can't be detected with single channel measurement during train pass-by.

The braking noise was measured for electric passenger trains stopping at the train station. It was discovered that the occurrence of high-level tonal squeal noise is strongly dependent on the braking intensity. It is possible to stop the train without any noticeable increase in the noise levels if low braking force is applied in a due time. An example of such successful braking is shown in Fig. 45 as pass-by noise spectrum comparison of braking and non-braking electric trains in the same place and the speed of 60 km/h (Fig. 44).

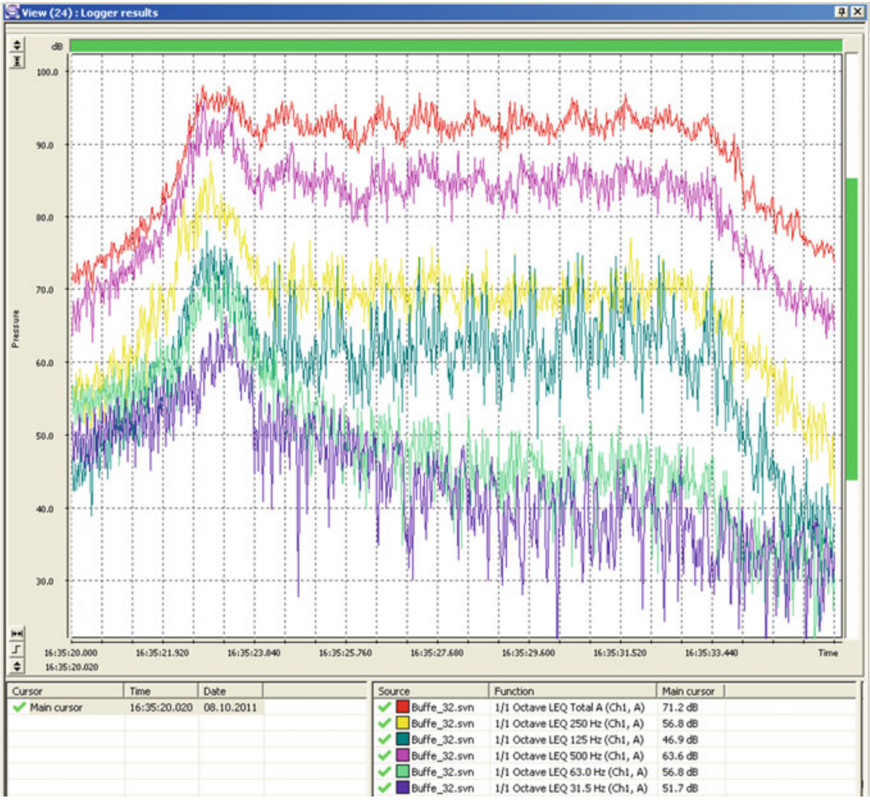


Fig. 42 Pass-by noise levels of diesel passenger train

About 10 dB(A) increase in 16 kHz octave band is seen, but it does a very little impact in total noise level. For better evaluation, the braking train pass-by noise spectrum in the time and frequency domain is shown in Fig. 46.

An example of unsuccessful braking noise spectrum of the electric train with the starting speed of 49 km/h is shown in Fig. 47.

The high-level tonal braking squeal noise is seen in the 8 kHz octave band, increasing the total noise level by about 10 dB(A). For Latvian railway rolling stock the dominating braking noise frequency found to be higher than 4 kHz. The effect of braking noise is better shown in Fig. 48.

The noise levels in other octave bands are reduced with decreasing speed, as shown in Fig. 49. In this figure we can also see that the 250 Hz octave band (in yellow) is the main frequency of stationary noise from the electric train (end of the measurement) and remains important during all train pass-by.

One more interesting example of electric train braking noise is shown in Fig. 50. Here we can see that first the 8 kHz (yellow) and 4 kHz (blue) were dominant octave bands for braking noise, however at the end of measurement (end of braking) the

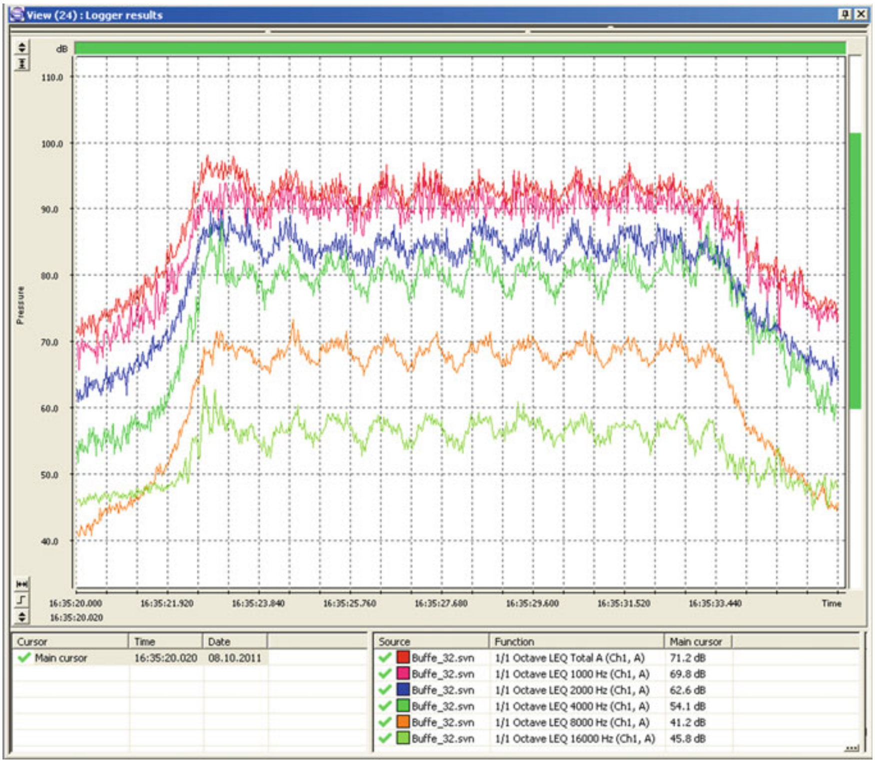


Fig. 43 Pass-by noise levels of diesel passenger train

16 kHz octave band became dominant. High level noise at this frequency is very annoying both for people inside and outside the train. Moreover, the braking squeal noise might be linked with blocked and sliding rather rolling wheel pairs and points out on the increased deterioration of the brake system, wheels and rails. Such braking will increase the rail surface roughness at the train station and therefore also the pass-by noise from non-braking trains. Since train stations are often placed directly in the cities this problem requires proper attention. All drivers should be trained and follow instructions how to minimize the braking noise.

The curve squeal and impact noise on rail joints being specific railway noise problems were not in the list of current research tasks, however some investigation of impact noise from rail joints has been undertaken. Latvian railway during last few years has rapidly increased the amount of jointless rails over the rail network, therefore the problem of impact noise becomes less important. Only in the places where due to some reasons it is currently not possible to eliminate the rail joints, they stay in place. Yet, it is essential to evaluate by how much the rolling noise level could be reduced eliminating the rail joints.

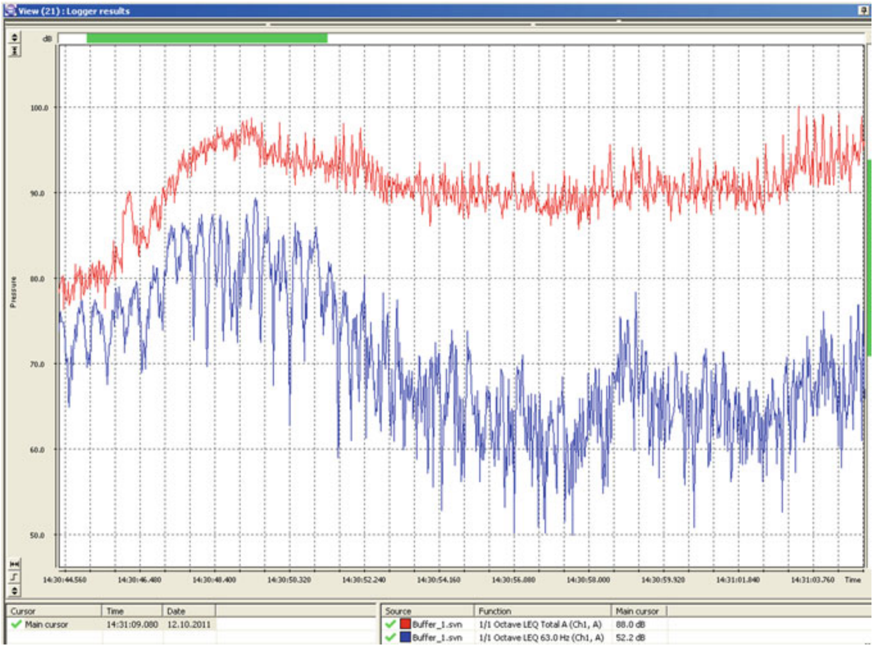


Fig. 44 Pass-by noise levels of accelerating freight train with average speed of 49 km/h

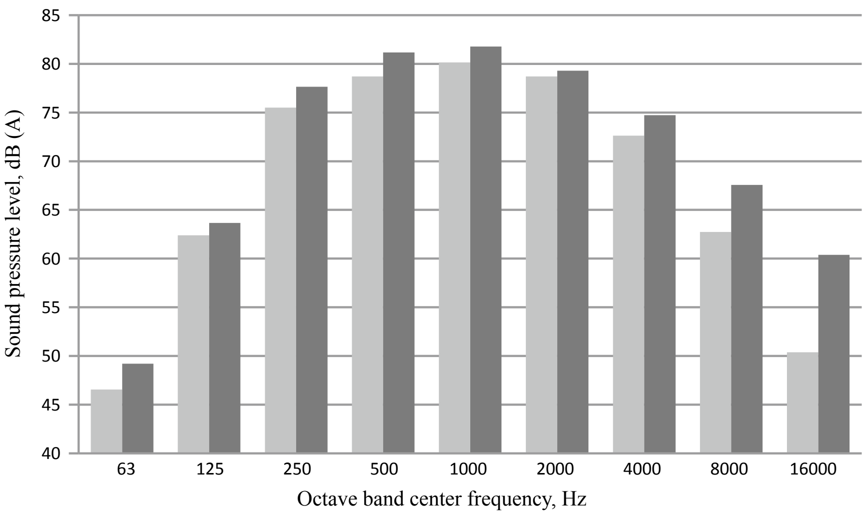


Fig. 45 Pass-by noise spectrums of braking (dark) and non-braking (light) electric trains

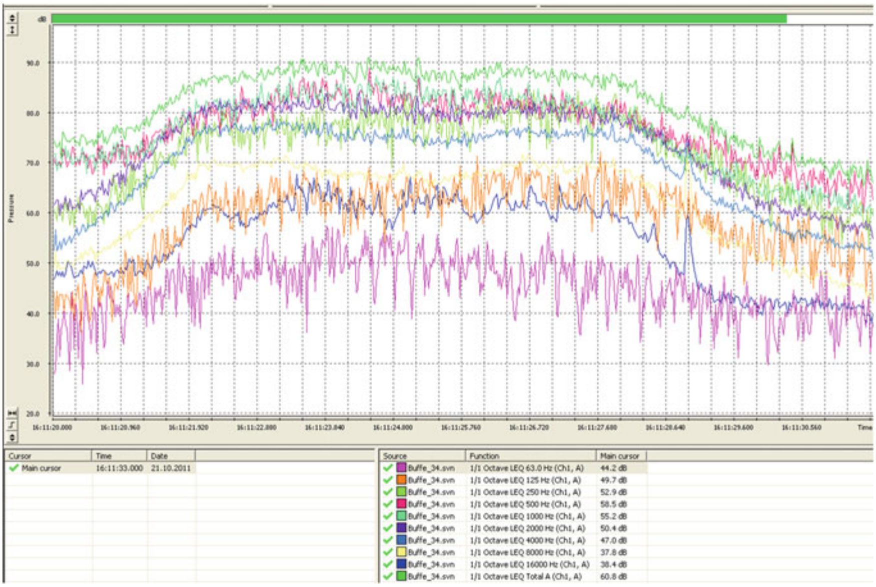


Fig. 46 Pass-by noise spectrum of braking electric train in the time/frequency domain

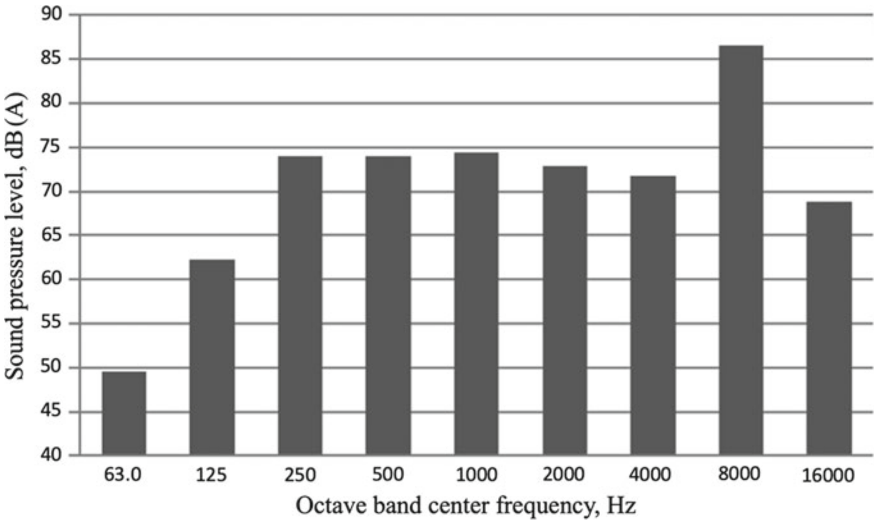


Fig. 47 Electric train braking noise spectrum

Fig. 48 Electric train braking noise in time and frequency domain

Each rail joint has a gap between two jointed rails. The increase in rolling noise level is strongly dependent on the width of the gap between rails and the difference in heights between rolling surfaces of jointed rails. The problem is that due to physical laws and railway maintenance instruction joint geometrical parameters (gap width can change from 0 to 31 mm) can change in time. Thus, the impact noise on rail joints should be investigated in each case separately. In Fig. 51 is shown example of the electric train pass-by noise level increase due to rail joint shown in Fig. 52.

Here it is important to mention, that measurements were made for two different electric trains of the same length and speed, therefore it is hard to evaluate the correlation between measurement results. Other, not visible track conditions could also be different between two measurement places, so this comparison should be treated only as a possible case, when the total pass-by noise level was increased by about 12 dB(A). The most important finding here is that the noise levels are increased in all octave bands rather than at low frequencies as it could be expected.

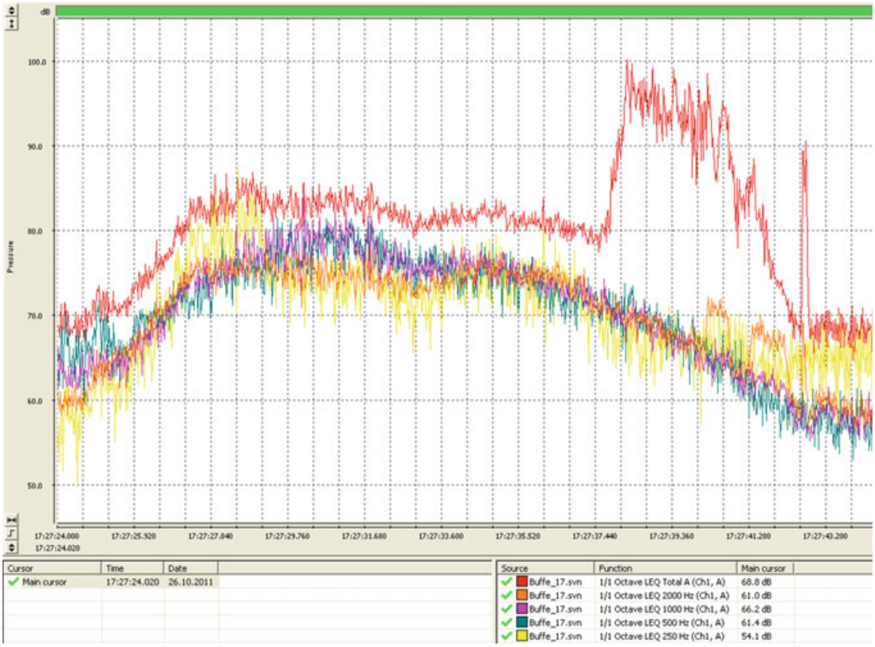


Fig. 49 Electric train braking noise in time and frequency domain

4 Comparable Analysis of Measurement and Modelling Results

In this section the experimental investigation results of railway noise on Latvian railway will be compared with results of modelling using the RMR method.

For modelling purposes, the CadnaA noise mapping software was used. In addition, software for spectrum calculation in the point of reception using RMR octave band method—Train Noise Software (TNS) was developed and was used as a part of RMR methods adaptation process. Let us first compare experimental investigation results with CadnaA modelling results.

In Figs. 53, 54, 55 and 56 correspondingly are shown measured and calculated using CadnaA spectrums for diesel passenger train, electric train, freight wagon train and freight train, assuming that the ground absorption factor is equal to 0.5 [8].

CadnaA calculates equivalent A-weighted noise spectrum and total level in the point of reception for a certain period of time. To compare calculation results with measurement results, the number of trains in CadnaA was taken proportionally to the measurement time using the following formula:

$$Q = \frac{3600}{T} N, \quad (54)$$

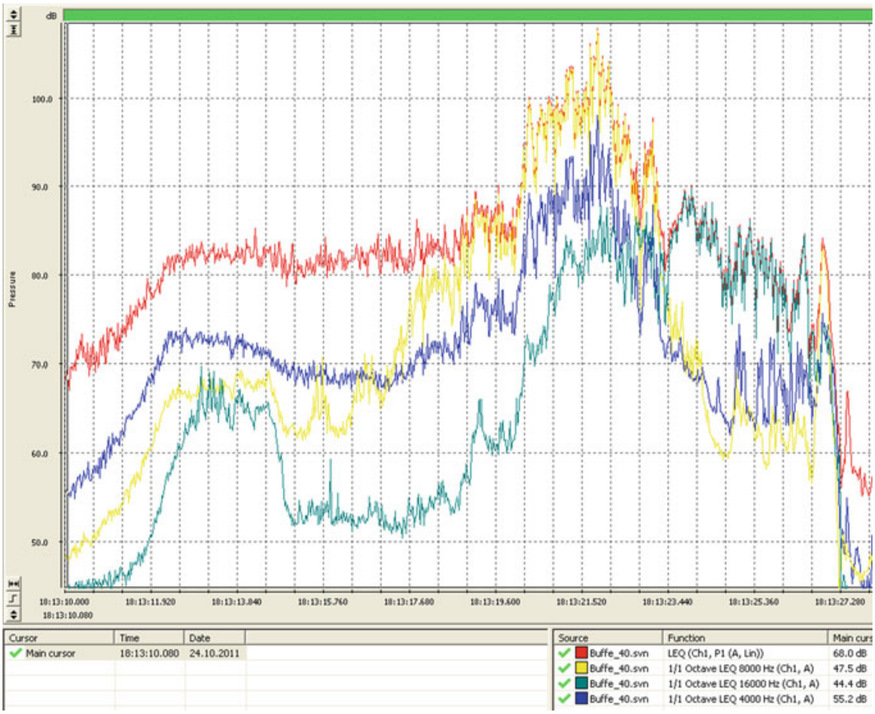


Fig. 50 Electric train braking noise in time and frequency domain

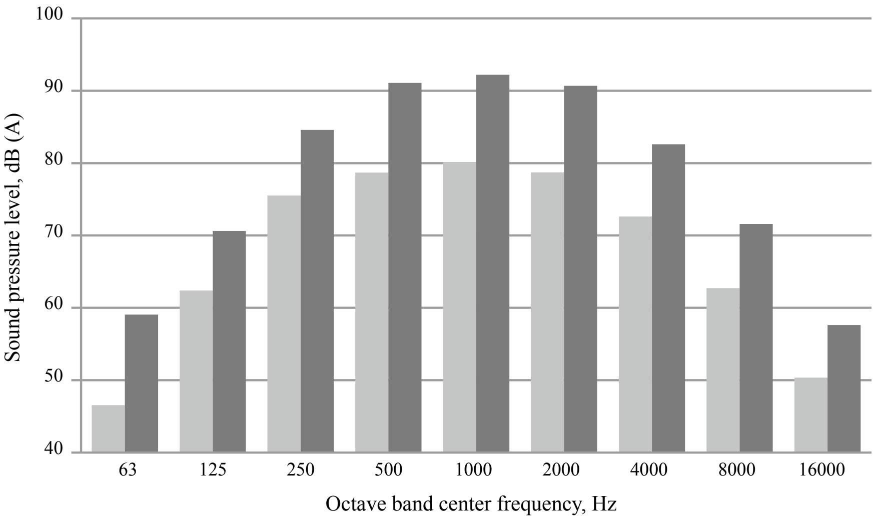


Fig. 51 Electric train pass-by noise spectrums dark—rails with joint; light—jointless rails

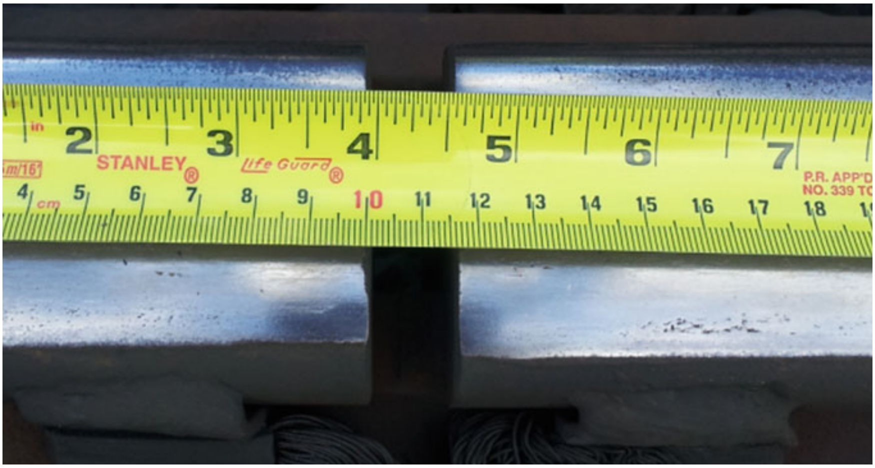


Fig. 52 Rail joint gap at the measurement place

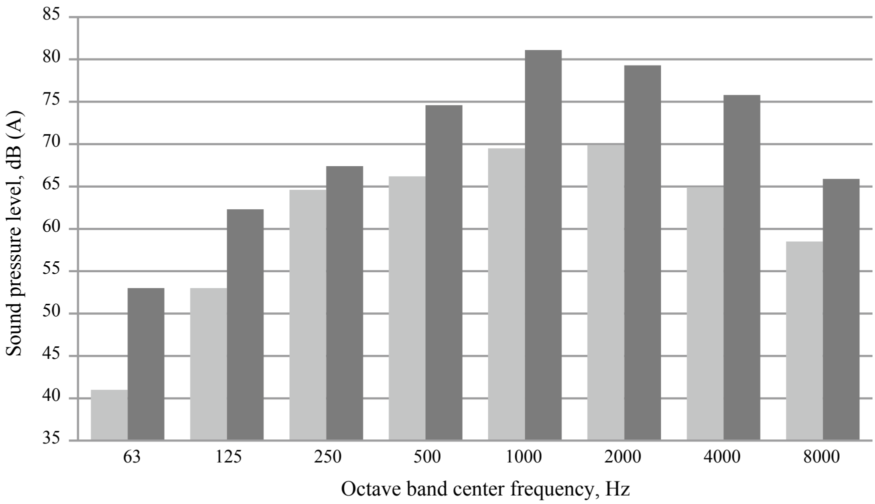


Fig. 53 Measured (dark) and CadnaA calculated (light) spectrums of diesel passenger train pass-by noise train speed—80 km/h, measurement time—5.7 s, RMR train type category 6

where

Q number of trains as input data for CadnaA calculation;
T measurement time, s;
N period of time for calculations, for the day N = 12, h.

The measured noise levels are higher than calculated in all octave bands by 2.8 dB(A) (250 Hz)—11.6 dB(A) (1 kHz). The total difference is 9.8 dB(A).

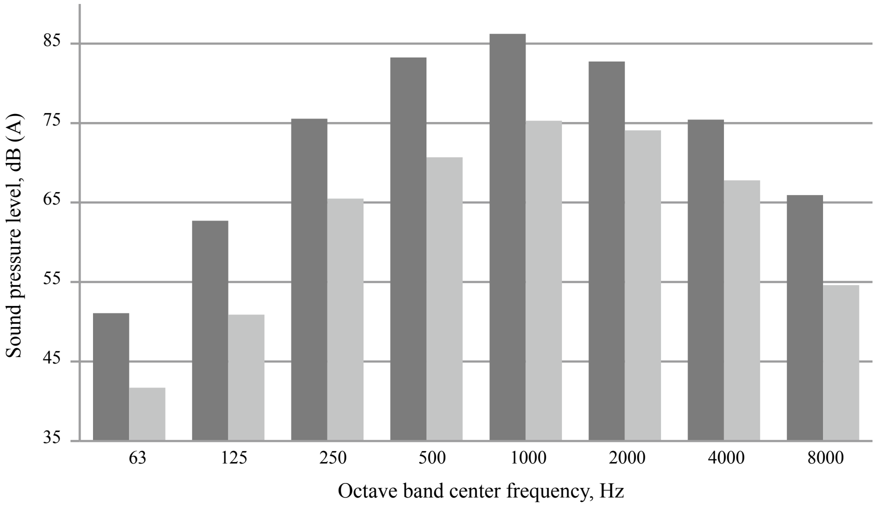


Fig. 54 Measured (dark) and CadnaA calculated (light) spectrums of electric train pass-by noise train speed—77 km/h, measurement time—5.9 s; RMR train type category 1

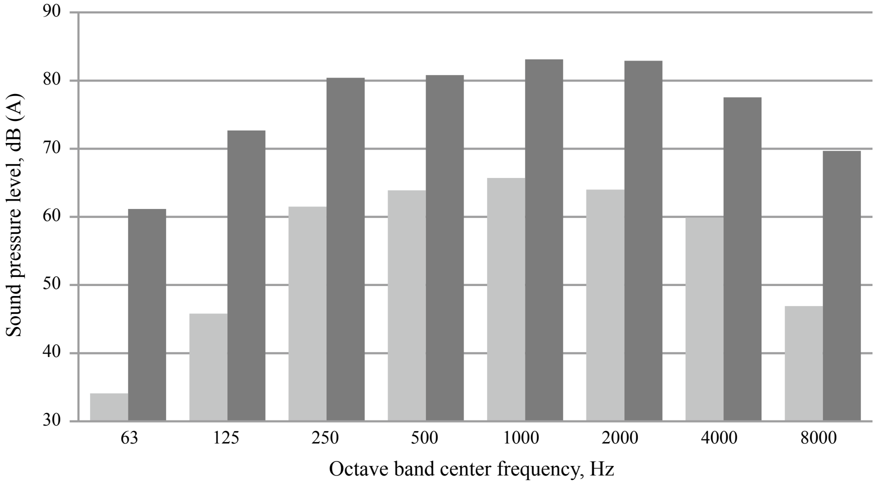


Fig. 55 Measured (dark) and CadnaA calculated (light) pass-by noise spectrums of freight train consisting only from wagons: train speed—65 km/h, measurement time—46.5 s; RMR train type category 4

The maximum in measured spectrum is in 1 kHz octave band, while in calculated spectrum it is in 2 kHz. There is no low-frequency engine noise peak in measured spectrum at 250 Hz as in calculated spectrum. If the RMR train type category for diesel passenger train with engine noise is used for modeling, the difference in total noise levels is decreased by 3 dB(A), but spectra shape lines differ more due to

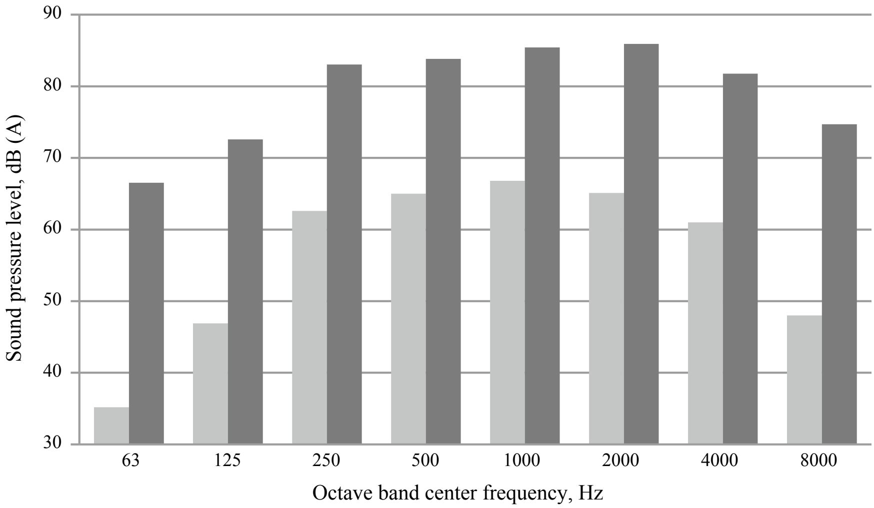


Fig. 56 Measured (dark) and CadnaA calculated (light) spectrums of freight train pass-by noise train speed—65 km/h, measurement time—36.5 s, RMR train type category 4

calculated low-frequency and 2 kHz peaks being even more expressed. In this case, the engine noise correction is essential for Latvian diesel passenger trains, only at higher speeds and at lower frequencies.

The measured noise levels are higher than calculated in all octave bands by 7.6 dB(A) (4 kHz)—12.6 dB(A) (500 Hz). The total difference is 10.3 dB(A).

The difference between calculated and measured electric train total noise levels is only 0.5 dB(A) more than in diesel passenger train case. The calculated spectrum shape shows to be a good fit to measurement results.

The measured noise levels are higher than calculated in all octave bands by 17.4 dB(A) (1 kHz)—27.1 dB(A) (63 Hz). The total difference is 18 dB(A). Biggest difference in first two octave bands must be due to traction noise and higher axle load. There is no peak in 2 kHz octave band in the calculated spectrum.

The measured noise levels are higher than calculated in all octave bands by 18.6 dB(A) (1 kHz)—31.3 dB(A) (63 Hz). The total difference is 19.7 dB(A).

In general, calculated noise spectra shape lines follow measured spectra shape lines precisely enough, but noise levels are underestimated in all octave bands. As expected, the biggest difference between measured and calculated noise levels is in case of freight trains. The lowest difference between total calculated and measured equivalent A-weighted noise levels found to be in case of diesel passenger trains.

Another important finding is linked to the RMR feature—calculated noise levels are traffic intensity dependent, but not directly train length dependent. Let us compare calculated freight train spectrums in Figs. 55 and 56. The only change in calculations is the traffic intensity depending on the measurement time. In real situation, the measurement time does not affect the measured equivalent sound level value of a single statistically constant source. But due to empirical RMR method character, we

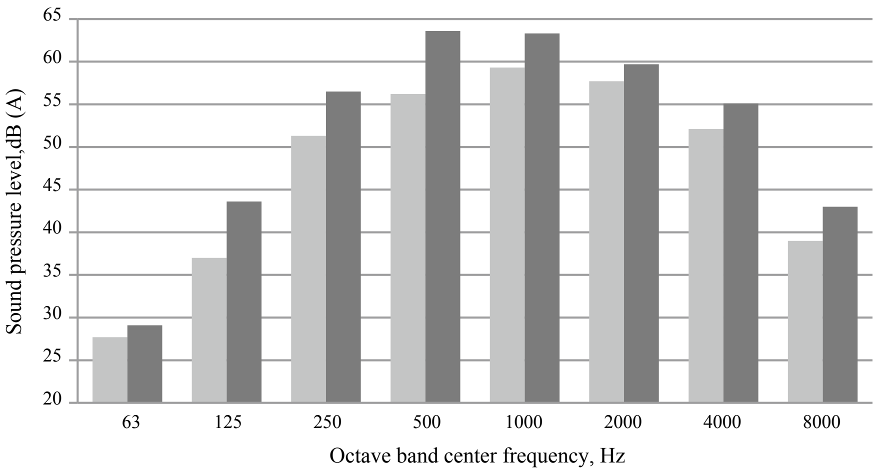


Fig. 57 Pass-by noise spectrums, track with joints (dark) and jointless track (light)electric train, train speed 60 km/h, pass-by time 7.2 s

get different spectrums for different measurement times. Now compare calculated spectrums for freight trains with spectrums for electric and diesel passenger trains—predicted noise levels for freight trains are lower than predicted noise levels for electric and passenger trains. Freight trains are longer, thus having longer pass-by time and as a result—lower number of trains (lower traffic intensity Q) used in calculation comparing to electric and passenger trains. This is not true for a real case.

For calculation of the increase of pass-by noise levels due to rail joints, RMR provides correction coefficients for track with jointed rails. These correction coefficients were obtained empirically for tracks and trains of Dutch railways. In Fig. 57 are shown CadnaA calculated electric train pass-by noise spectrums for jointless track and track with joints [11].

The total CadnaA calculated increase is 4.5 dB(A), mainly due to increased levels in low frequency range. As it was considered in previous section, on Latvian railway rail joints can significantly increase noise levels in all octave bands.

The braking noise in RMR is train type, speed and traffic intensity dependent. The CadnaA calculated increase in noise levels due to electric train braking is shown in Fig. 58.

In this particular case, the total level is increased by 4.5 dB(A) as in case with rail joints, but due to level increase at high frequencies. In previous section we have discovered that Latvian trains may be stopped without considerable increase in noise levels, however if the braking squeal occurs, the main level increase is found in 4, 8 kHz and even 16 kHz octave bands. The correction coefficients can be redefined for 4 and 8 kHz octave bands, but the 16 kHz octave band is out of RMR area of interest.

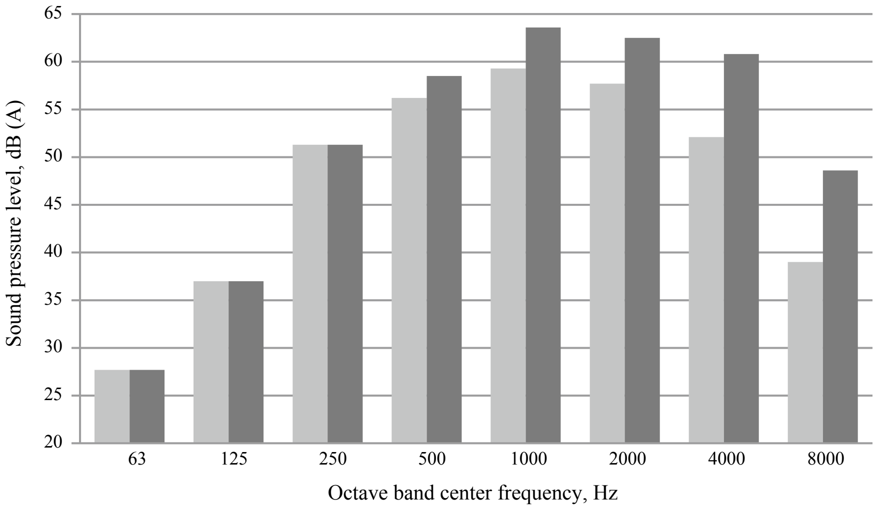


Fig. 58 CadnaA calculated pass-by noise spectrums for braking (dark)and non-braking (light) electric train speed 60 km/h, pass-by time 7.2 s

5 Conclusion

Research results had shown that some improvements to RMR method can be recommended to improve the applicability of the method:

– Squeal noise modelling might be added for better noise situation modelling near railway turns;
– Locomotive idling noise modelling for areas close to shunting yards;
– Extending octave band spectra up to 16 kHz to cover tonal braking noise;
– Separation of freight train type category into subcategories;
– More detailed description of rail joint influence to rolling noise.

Though, the new European Directive 2015/996, published the 1st of July, replaces the Annex II of the Directive 2002/49/EC. The directive defines the new common noise assessment methods that should be used in each Member State from 31/12/2018 for each kind of noise sources (road, rail, aircraft, helicopter etc.).

It is essential for all EU member states to be prepared on time for new modelling method implementation. And even if the RMR method is being improved for application in local railway conditions, it is required to start the evaluation of the new CNOSSOS proposed method.

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