Article

Environmental assessment of the vehicle operation process

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Abstract: The environmental safety of a car is currently one of the most important indicators of the vehicle competitiveness and quality in the consumer market. Currently, the assessment of the ecological properties of vehicles can be made based on various criteria. In the case of combustion-powered cars, the most attention is usually paid to the values characterizing their use, and in the environmental assessment, first of all to pollutant emissions and operational fuel consumption. The proposed article considers the possibility of using the life cycle assessment to analyze the ecological properties of a passenger car during its operation. A simplified LCA method of the vehicle was presented, which in strictly defined cases can be used for the analysis of environmental impacts and the assessment of the energy analysis related to its operation. For this purpose, a vehicle life cycle model was developed. Data on the operation of 33 passenger cars of different manufacturers with similar operational characteristics, coming from different production periods, were analyzed in detail. The obtained results were found to be highly sensitive to the assumptions made in the article.

Keywords: internal combustion engine vehicle, life cycle assessment (LCA), energy analysis

1. Introduction

The global automotive industry is currently facing a serious challenge of the ongoing global environmental degradation. Currently, there is no doubt that road transport - next to the energy sector - is one of the greatest threats to the environment, related to both the systematic increase in global carbon dioxide (CO_2) emissions and the increase in the amount of waste generated during the production and disposal of end-of-life vehicles. Concerns about the negative environmental impact of car transport are exacerbated by the constantly growing number of cars in the world. Legal regulations aimed at eliminating environmentally harmful technologies are used to reduce environmental degradation by road transport. Stricter environmental standards put the automotive industry under increasing pressure to reduce fuel consumption and exhaust emissions over the lifetime of a car. Hence, most of the research described in the world literature focuses on reducing energy consumption and emissions of toxic compounds and CO_2 directly related to car operation. Most often they involve an environmental impact assessment of unconventional drives or alternative fuels.

There are many methods for assessing the ecological properties of a car. In the case of cars with internal combustion engines, the traditional approach to environmental assessment is primarily to determine CO_2 emissions, which depend on the type and amount of fuel consumed. The research methods of these quantities are largely objectified, they have a long tradition in the automotive industry and are based on extensive knowledge. The effect of this approach are the existing EURO standards. The methodology (LCA) described in the ISO 14040 [1] and 14044 [2] standards expresses a contemporary approach to the problem of the car's impact on the environment and has been used for this purpose for over 30 years [3]. It is used to determine the potential environmental impact of the processes related to the entire contractual lifetime of the car, from the production of materials, through the production of the car, its operation to its decommissioning. There have been many studies that evaluate the car from the point of view of life cycle analysis. Most of the work is devoted to the environmental assessment of the vehicle construction phase. Most often, individual components or assemblies of a car are the subject of a detailed life cycle assessment (LCA) [4]. Other research has focused on a car design for the ease of assembly. Estimates on the share of individual processes in the environmental loads of the car throughout its life cycle are also presented. They show that the car operation process has a dominant impact on energy consumption and the amount of pollutant emissions [5]. Since then, there has been a lot of work on the assessment of the impact of car use on the environment. Among the many effects of the automotive industry's impact on the environment, the most attention is paid primarily to air pollution by toxic substances emitted from vehicles, which pose a threat to human health [6, 7] and to the growing consumption of limited resources of fossil fuels [8]. Other studies indicate the high effectiveness of the car's curb weight strategy in order to reduce the environmental impact during its operation [9]. Without a doubt, these problems continue to grow as the demand for means of transport is now increasing. According to the Regulations of the United Nations Economic Commission for Europe (UNECE), air emissions from the transport sector currently account for about 23% of total anthropogenic CO_2 emissions on a global scale [10]. The number of light duty vehicles is expected to increase from around 1.3 billion by 2030 to 2 billion by 2050, which could also lead to a significant increase in demand for gasoline and diesel in the coming years, and which will undoubtedly have an impact on energy security, climate change and air quality not only in cities but also outside them [11]. In this context, sustainable development has become a very important issue for the automotive industry, motivating the transport industries to significantly reduce the overall environmental impact of vehicles, especially during the operation. The most attention is paid to the environmental assessment of car drive technologies, most often analyzing fuel efficiency in terms of minimizing the consumption of materials and energy [12]. Much emphasis is also placed on the use of batteries in electric vehicles (BEV), which are now treated as a real solution contributing to environmental protection by reducing the use of fossil fuels [13]. For this reason, currently, the most frequently presented studies in the literature are the ones comparing the ecological profile of vehicles with various drive technologies, such as internal combustion engine with purely electric and hybrid cars [14, 15]. There are many studies that are focused only on specific elements of the vehicle, such as the battery [16, 17, 18], but it is still confidential information based on the materials available in the literature. Several studies have assessed the impact on the environment not only the drive unit of the vehicle. They included material inputs for the entire vehicle, and on this basis, an analysis was made throughout the entire life cycle, including the operation phase [19, 20, 21, 22]. In these studies, the inventory data contained in the literature is most often used, and on this basis, the environmental impact of the car is assessed. In addition, the most frequently studied phase is the vehicle production phase, mainly the production of the powertrain. The comparison of the environmental profile of conventional and electric cars is also presented in [23, 24, 25]. Along with the development of civilization, the awareness of the current environmental threats and the great need to counteract them increases. This is particularly evident in the automotive industry, where the environmental issues have recently become more and more important. Currently, the ecological properties of vehicles, in addition to the safety systems used, are often considered to be indicators of technical progress in the automotive industry. The problem of vehicle use and its impact on the environment is becoming more and more serious nowadays due to the constantly growing transport needs [26]. It is much easier to minimize the negative effects of stationary emission sources than the effects of many millions of moving vehicles. The aim of the article is to propose a model of the environmental impact of the car operation phase. Using the developed model, selected aspects of its ecological evaluation in operating conditions have been presented.

2. Modeling the car operation phase

2.1. Purpose and scope of research

The environmental assessment of a vehicle under operating conditions presented in the article is based on a passenger car life cycle model that uses LCA analysis in accordance with the requirements of ISO 14040 and ISO 14044. The environmental assessment of the operation phase is presented on the example of 30 passenger car models of the same generation, manufactured since 1984, with comparable operating characteristics. These were the front-wheel drive vehicles with a manual gearbox. The vehicle use model takes into account the environmental load due to fuel consumption and pollutant emissions from the internal combustion engine as well as the processes related to the maintenance of the car. The assessment of these processes provides for the supply of additional material streams needed to carry out periodic maintenance and emergency repairs. In order to ensure the comparability of the evaluation results, the cars with a gasoline engine with a capacity of 1.2 to 1.5 dm3, standard equipment and comparable performance were adopted. The bodies of these vehicles are a three- and five-door hatchback and a four-door sedan. They were produced and operated in the years 1984–2013. These years have been divided into five six-year periods. For each period, 4 to 8 vehicles of different brands were assigned, for which the average results of the analysis were presented in three adopted categories of environmental impact: material consumption, energy consumption and the accompanying emission levels. Each subsequent passenger car of a given brand was the successor of the previous model. Due to the high complexity of the structure and the lack of detailed data on the production processes, the energy and ecological characteristics of the vehicles in question were determined on the basis of the results of a detailed inventory of materials with known characteristics used for their production. This approach allowed, among others conducting a detailed comparative analysis of the environmental loads characterizing vehicles from different manufacturers with their changes in the material structure of vehicles in the considered time period and the assessment of the possibility of pro-ecological rationalization of car production in the future. During a detailed analysis, 27 material groups were identified, the total environmental loads of which in terms of energy consumption and emission levels amounted to 95% of the environmental impact of the total mass of raw materials involved in the vehicle manufacturing process. The characteristics necessary for the analysis of the selected material groups were obtained from the available databases: Gemis and LCA Plastics Europe Report and from supporting calculation programs: SimaPro and Greet. The energy inputs and emission levels in the operation phase of the selected cars related to fuel consumption were assessed on the basis of the technical data of the tested vehicles, in which the average fuel consumption is determined according to the measurement method of the United Nations Economic Commission for Europe described in the ECE R83 regulation.

The basic assumption of the presented model is the analytical modeling of the production phase of a passenger vehicle shown in Figure 1, which in the first stage includes its division into assemblies (A), which are then divided into sub-assemblies (S) consisting of individual materials (M) with a specific mass (m). These materials are grouped into five basic groups: ferrous metals, aluminum and its alloys, plastics, non-ferrous metals and other materials. Determining the material structure of a motor vehicle is the basis for determining the amount of energy and ecological inputs for individual types of materials, including the materials used for the car's operation phase. The vehicle use model takes into account the environmental load resulting from fuel combustion in the internal combustion engine during the actual car driving. The processes related to the maintenance of the car and the processes related to the production and delivery of fuel were taken into account.

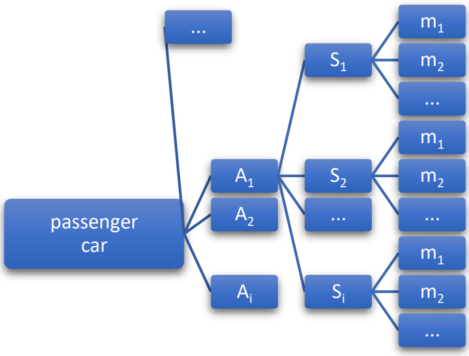

Figure 1. Analytical model of passenger car decomposition

According to ISO 14040 (2006), LCA covers all stages of the life cycle, from creation to disposal of a product or service, from raw material extraction, through production and use, to waste management. In all phases of the life cycle, energy and natural resources are used and pollutants are released into the environment. In line with the aim of our research, in order to be able to effectively compare the environmental profiles of cars in such a long time perspective, we limited the scope of the assessment to the processes and material streams directly related to the production of materials, the use of the car and the end of its life. On the other hand, the impact of production and transport infrastructure have been ignored. This means that only during these processes, substances that are released to the environment exceed the system boundaries covering the entire life cycle (production, use and recycling phase of the car).

2.2. Model inventory data

The operation of passenger cars is a set of deliberate organizational, technical and economic activities of people with the vehicle and the relations between them, from the moment of taking over the vehicle for use in accordance with its intended use, until its liquidation. The service life of the vehicle is primarily its use and maintenance. The operational use of a vehicle is an activity related to its intended use. During use, the car is subject to wear processes leading to a change in its technical condition. It is therefore necessary to take appropriate actions related to the maintenance of the vehicle so that it can be safely used for its intended purpose. In the concept of maintenance, we can distinguish activities related to checking the condition of the vehicle and preventing excessive and premature wear (called maintenance) as well as the activities consisting in removing the effects of wear and restoring the vehicle's condition (called repair). In practice, the boundary between maintenance and repair is often negligible, which is why both activities are called maintenance. All maintenance during vehicle operation should be performed regularly in cycles depending on the mileage of the vehicle, its operating time, the seasons of the year and the occurrence of special operating conditions, such as: external temperature, humidity, dustiness and increased intensity of use. The vast majority of maintenance cycles are related to the actual mileage of the vehicle, measured with the on-board odometer. This meter relatively accurately reflects the actual wear process of mechanisms and consumables used. Vehicle designers strive to minimize the frequency of necessary maintenance for the convenience of users. However, maintenance cycles of tens of thousands of kilometers traveled oblige, in turn, the user to keep appropriate documentation of the treatments performed and to accurately track the meter readings. In this respect, it is more convenient to conduct services in seasonal cycles, in line with the natural cycles of nature or with the administrative cycles of periodic technical inspections.

Data for the environmental assessment of the vehicle operation process was obtained during tests carried out at a certified disassembly station in Szczecin (Poland). Data obtained from the literature was also based [27, 28]. As part of the research, the cars were disassembled into assemblies and individual parts. In order to prepare the list of materials used in the cars, the parts were weighed and the type of material used was determined. Many small parts were made of one material and similar technology. In this case, in the list of parts, their total weight was expressed in kilograms. The missing material data for some car components, such as plastic and rubber body fittings, was obtained from the IDIS vehicle manufacturer's database.

2.3. Assumptions of identification research

In order to quantify the environmental impact of the vehicle in three selected impact categories, the model of the vehicle construction phase was identified on the basis of the collected research material covering 33 selected vehicles from different manufacturers belonging to the B and C segments, which were produced in the years 1984–2013. It required the determination of the mass of materials constituting each vehicle immediately after leaving the manufacturer's assembly plant. It was assumed that on the basis of changes in the material structure, the level of energy consumption and emissivity in the vehicle construction phase in subsequent years of their production, which were divided into five six-year periods, can be determined. The environmental loads generated during the operation phase were defined as not related to the material structure of the car, but depending on its own weight and the design features of the engine and drive system. This means that for vehicles belonging to the same class and of a similar design, the level of environmental impacts during their operation can be considered comparable in the comparative analyzes carried out. Based on changes in material inputs, an analysis of energy consumption and emissivity was carried out within the adopted categories of environmental impact. The obtained characteristics, indicating changes in the magnitude of the generated environmental loads, were determined for the entire vehicle and divided into individual groups and material groups.

Figure 2 shows changes in the mass of selected cars in relation to the production years along with the marked periods. The significant dispersion of the weight of vehicles of different manufacturers in particular production periods is noteworthy. In order to confirm the correlation between the vehicle weight and production years, on which the analysis of the car operation phase was based, in the entire range from 1984 to 2013 and in individual production periods, the Spearman’s rank statistical test was performed. For this purpose, specialized software Statistica 10 PL was used. The results of correlation studies for the adopted significance level (*p=0,05*) are presented in Table 1.

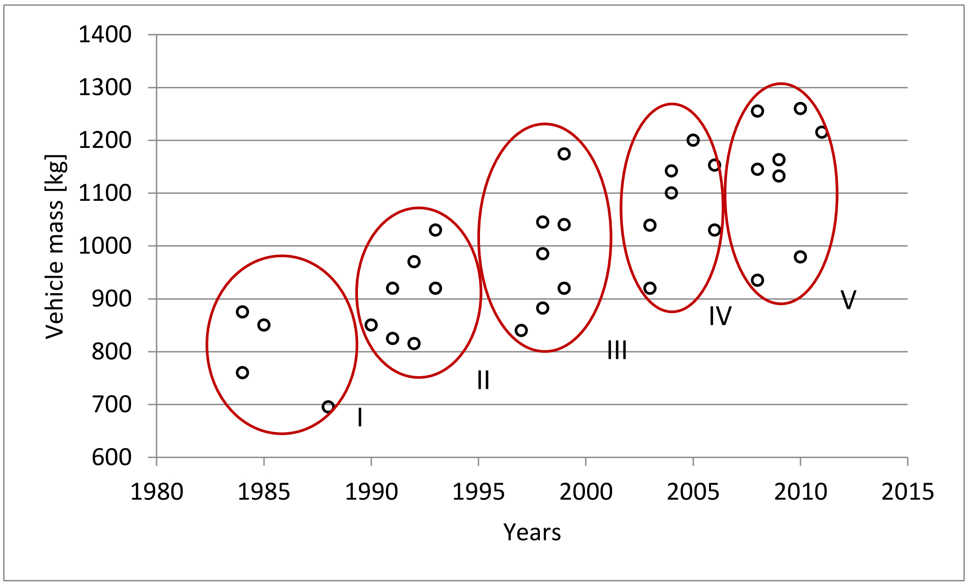

Figure 2. Mass dispersion of passenger cars in relation to the years of production

Table 1. Spearman's rank correlation results for vehicle weight and years of production

A pair of variables: Mass & Years	n	R Spearman	t(n-2)	p
all	33	0.806	7.57	<0.0001
1984-1989	4	-0.632	-1.15	0.3675
1990-1995	7	0.500	1.29	0.2531
1996-2001	7	0.579	1.59	0.1735
2002-2007	7	0.624	1.79	0.1342
2008-2013	8	0.457	1.26	0.2548

Table 1 gives the size of the groups in the column *"Valid n"*. The *"R Spearman"* column shows the value of the *Spearman's R* coefficient, in the column *"t(n-2)"* - the value of the *t* statistic checking the significance of this coefficient, and in the column *"p"* - the significance level for the above *t* statistic. There is a statistically significant relationship between the weight of all vehicles and the years of production. The correlation is positive and its value is *R=0.81*, which means that the higher the year of production, the greater the vehicle weight. In contrast, there were no statistically significant correlations between the mass of vehicles in the examined periods of production *p>0,05*).

Thus, the obtained results indicate the permissibility of dividing the production years into five six-year periods.

The average weight of passenger cars was determined for each period of production years. In the analyzed period from 1984 to 2013, the average weight increased by approximately 340 kg. This corresponds to a weight increase of about 43%.

Table 2. Average weight of passenger cars

Years of production	n	Average [kg]	Standard deviation [kg]
1984–1989	4	795.0	83.0
1990–1995	7	904.3	79.4
1996–2001	7	983.7	114.2
2002–2007	7	1083.4	94.6
2008–2013	8	1135.5	120.5

Figure 3. The average weight of passenger cars (including standard error and standard deviation) in relation to the years of production

In order to check whether there is a difference in the average level of the weight of motor vehicles in the analyzed periods of production years, the non-parametric Kruskal-Wallis test was used, assuming the statistical significance level *p=0,05*. The results of the statistical analysis are presented in Table 3.

Table 3. Kruskal-Wallis test results

Independent variable: Years of production Kruskal-Wallis test: H (4, n= 33) =18,71; p=0,0009				
Dependent: Vehicle weight	**Code**	**n**	**Sum of ranks**	**Average ranks**

1984-1989	101	4	17.5	4.4
1990-1995	102	7	70.0	10.0
1996-2001	103	7	114.5	16.4
2002-2007	104	7	155.0	22.1
2008-2013	105	8	204.0	25.5

The first column shows the periods of the production years of motor vehicles. In the *"Code"* column - data rank code for each period. The column *"Valid n"* shows the number of passenger cars tested, the columns *"Sum of ranks"* and *"Average ranks"* – the sums and average ranks for each period. The determined value of the Kruskal-Wallis test (for 4 degrees of freedom and 33 tested motor vehicles) is $H=18.71$ at the level of statistical significance $p=0.0009$. These values confirm the statistical significance of the influence of the adopted production periods on the average weight of passenger cars manufactured in these periods. At the same time, the obtained results of the statistical analysis indicate the permissibility of determining the mass shares of selected material groups and the corresponding energy inputs and environmental loads on the basis of the average values of the mass of the vehicle and its components for each production period.

In order to determine the model description of changes in material inputs, the statistical method of regression analysis was used. The mathematical model is presented in the form of a regression function approximating empirical data that describes changes in the mass of a vehicle and its components in particular periods of car production. The accuracy of the approximation was assessed for the regression function in the linear ($y=a\cdot x+b$), power ($y=b\cdot x^a$), exponential ($y=b\cdot a^x$), quadratic ($y=a\cdot x^2+b\cdot x+c$), hyperbolic ($y=a\cdot\frac{1}{x}+b$) and logarithmic ($y=b+a\cdot log_{10}x$) forms. The estimation of the regression function coefficients was performed using the least squares method (LSM). The module of the Statistica program was used. The adequacy of the functional dependencies obtained in this way was verified on the basis of the *R* correlation coefficient.

In the case of the model describing the changes in vehicle mass in relation to the production years (Fig. 3), its distribution indicates the possibility of approximation using a linear function in the form: $y=a\cdot x+b$. The determined values of the coefficients of this function and the relevant statistics are presented in Table 4

Table 4. Results of regression analysis of the linear function for the whole vehicle mass

Model: Mass =b+a*Years Dependent variable: Mass; Independent variables: Years R²=0.622; R=0.789						
Parameter	**Rating**	**Standard error**	**t (df=31)**	**p**	**Lower confidence limit**	**Upper confidence limit**
b	-27545.5	3995.0	-6.90	$p<0.0001$	-35693.2	-19397.7
a	14.3	2.0	7.15	$p<0.0001$	10.2	18.4

The values of parameters a and b along with estimation errors are shown in the *"Rating"* and *"Standard error"* columns. The column *"t(df=31)"* shows the quotients of the evaluation and the error of parameter estimation for a given number of degrees of freedom *(df)*. The column *"p"* shows the value of the calculated test probability level of the significance of the parameters. In the columns *"Lower confidence limit"* and *"Upper confidence limit"*, 95% confidence intervals (lower and upper) of the estimated parameters a and b are given. Both parameters of the linear function model (a and b) are statistically significant (the calculated value of the probability level p is lower than the adopted significance level of 0.05), and the linear trend function explains the variability of the vehicle mass *"R^2"* in over 62.2%. Thus, the results of the verification of the adequacy of the regression function indicate a high accuracy of the description of vehicle mass changes using the selected approximation function.

Ultimately, the regression model describing the changes in the vehicle mass in the subsequent production periods along with the estimation errors is as follows:

$$\underset{(2,0)}{Mass = 14.3} \cdot \underset{(3995,0)}{Years - 27545.5} \qquad \text{(kg)} \tag{1}$$

Every year, the weight of motor vehicles increases on average by about 14.3± 2.0 kg.

3. Characteristics of changes in material and energy inputs and environmental loads in the vehicle operation phase

3.1. Assumptions for the annual vehicle operation

The following assumptions have been made for the analysis of the annual operation of the vehicle:

- annual mileage of motor vehicles: 15,000 kilometers,
- the scope of activities involving the replacement of operating fluids and car parts and subassemblies subject to normal wear and tear was determined on the basis of periodic inspection schedules established by the manufacturers of the tested brands and models of motor vehicles.

Assumptions for additional activities related to the cyclical replacement of components subject to wear and not included in the periodic inspection schedule:

- tire change - every 4 years (summer and winter)
- brake pad replacement - every 2 years,
- changing the windscreen washer fluid - twice a year (summer and winter),
- replacement of wiper blades - twice a year.

It was assumed that the oil in the gearbox and the oil in the power steering system do not need to be changed. A summary of the average weight of elements subject to cyclical replacement (according to manufacturers' recommendations) per 1 year of operation is shown in Table 5.

Table 5. Average material inputs for elements to be replaced per year

Replacement of components [kg/year]	**Production years periods**				
	1984–1989	**1990–1995**	**1996–2001**	**2002–2007**	**2008–2013**
Oil replacement	2.76	2.62	2.52	1.88	1.41
Oil filter replacement	0.65	0.64	0.55	0.37	0.30
Brake fluid replacement	0.20	0.18	0.17	0.28	0.31
Coolant replacement	1.22	0.86	1.07	0.52	0.67
Air filter element replacement	0.30	0.20	0.14	0.17	0.15
Cabin filter (pollen)	0.25	0.23	0.26	0.28	0.27

replacement					
Fuel filter replacement	0.55	0.33	0.28	0.22	0.22
Timing belt replacement	0.06	0.06	0.06	0.05	0.05
Spark plugs replacement	0.40	0.24	0.20	0.21	0.22
Tires replacement	12.42	12.56	12.64	13.52	12.84
Brake pads replacement	0.46	0.45	0.51	0.46	0.54
Windscreen washer fluid replacement	4.59	4.43	3.05	4.32	3.76
Wiper blades replacement	1.14	1.22	1.17	1.31	1.30
Gasoline (average consumption)	725.63	763.39	758.57	742.50	700.31

In the annual operation of a passenger car, petrol has the largest mass share among the elements to be replaced. The remaining elements account for a small part of the total material inputs incurred during the annual use of a car, which is about 3% for all vehicles produced between 1984 and 2013. The assessment of material inputs was supplemented with unplanned replacements of elements and assemblies of the vehicle of a random nature, which may occur at any time of the assumed vehicle operation period.

3.2. Energy inputs

On the basis of the average consumption of consumables and elements subject to cyclical replacement (Table 5), the corresponding energy inputs were determined. Table 6 shows the average energy inputs in subsequent production periods for the entire vehicle and for gasoline, assuming the annual operation period. A graphic illustration of these changes is shown in Figure 4.

Table 6. Average energy inputs in [MJ] for various production periods

EI [MJ]	**Production years periods**				
	1984–1989	**1990–1995**	**1996–2001**	**2002–2007**	**2008–2013**
The entire vehicle	6090	6334	6286	6088	5722
Gasoline	5703	6000	5962	5836	5505
Others	387	334	324	252	218

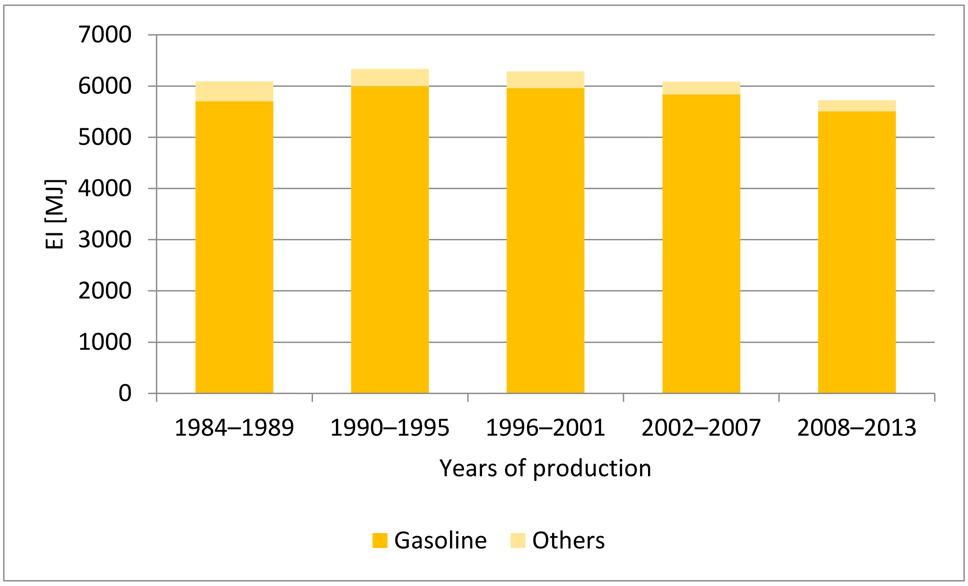

Figure 4. Energy inputs for the entire passenger car

The obtained values of average energy inputs for the entire motor vehicle in subsequent years of production are determined mainly by the inputs resulting from fuel consumption, which constitute from about 94% (1984–1989) to around 96% (2008–2013) of the total expenditure incurred during the annual vehicle operation. Although the percentage share of fuel inputs remains practically unchanged, their clear changes can be noticed in subsequent periods of car production. Initially, at the turn of the first and second period, an increase in these inputs by about 4% is observed. This is the result of the more and more common use of injection systems and catalytic reactors and the related enrichment of the mixture to a stoichiometric composition, leading to a certain increase in fuel consumption. However, as the design of engines that meet the more and more stringent requirements, including fuel consumption, has been improved, the related energy input in subsequent periods is reduced by about 8%.

3.3. CO_2 emissions

Table 7 presents the values of the average CO_2 emissions in the subsequent production periods related to the entire vehicle and to petrol, assuming the annual operation period. A graphic illustration of these changes is shown in Figure 5.

Table 7. Average CO_2 emissions in [kg] for different production years

CO_2 emissions [kg]	**Production years periods**				
	1984–1989	**1990–1995**	**1996–2001**	**2002–2007**	**2008–2013**
The entire vehicle	2913	3061	3041	2975	2805
Gasoline	2897	3048	3029	2965	2796
Others	16	13	12	10	9

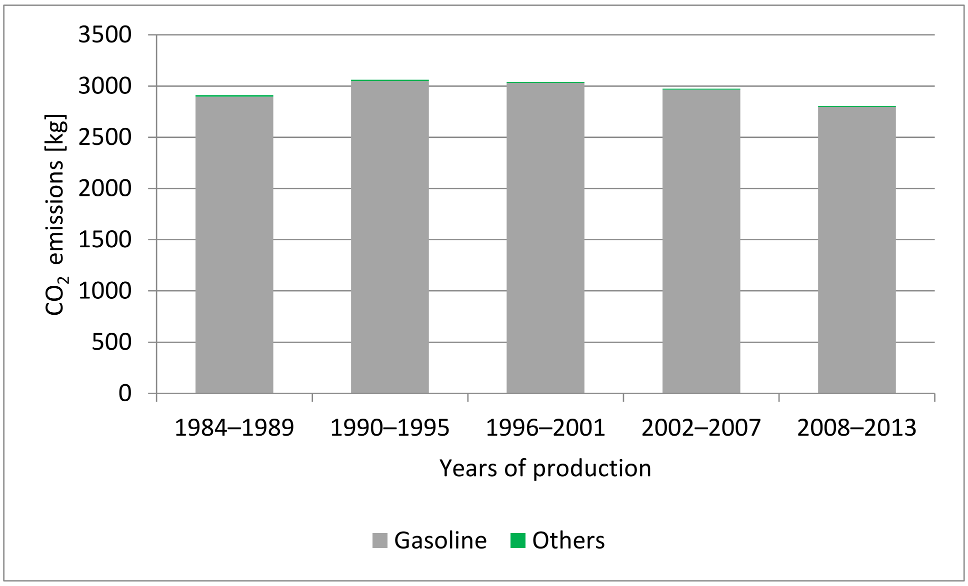

Figure 5. CO_2 emissions for the entire passenger car

As in the case of energy inputs (Fig. 5), fuel consumption, which accounts for over 99% of the total CO_2 emissions in the annual period of the car use, has a dominant influence on the level of average CO_2 emissions in cars from subsequent production periods. The observed changes in the levels of these emissions reflect the previously discussed changes in fuel consumption. Thus, after an initial increase in CO_2 emissions by about 5% in vehicles from subsequent production periods, the level of CO_2 emissions is reduced by around 8%.

3.4. SO_2 emissions

Table 8 presents the values of the average SO_2 emissions in the subsequent production periods related to the entire vehicle and to gasoline, assuming the annual operation period. A graphic illustration of these changes is shown in Figure 6.

Table 6. Average SO_2 emission in [kg] for different production periods

SO_2 emissions [kg]	**Production years periods**				
	1984–1989	**1990–1995**	**1996–2001**	**2002–2007**	**2008–2013**
The entire vehicle	8,16	8,57	8,52	8,33	7,86
Gasoline	8,12	8,54	8,49	8,31	7,84
Others	0,04	0,03	0,03	0,02	0,02

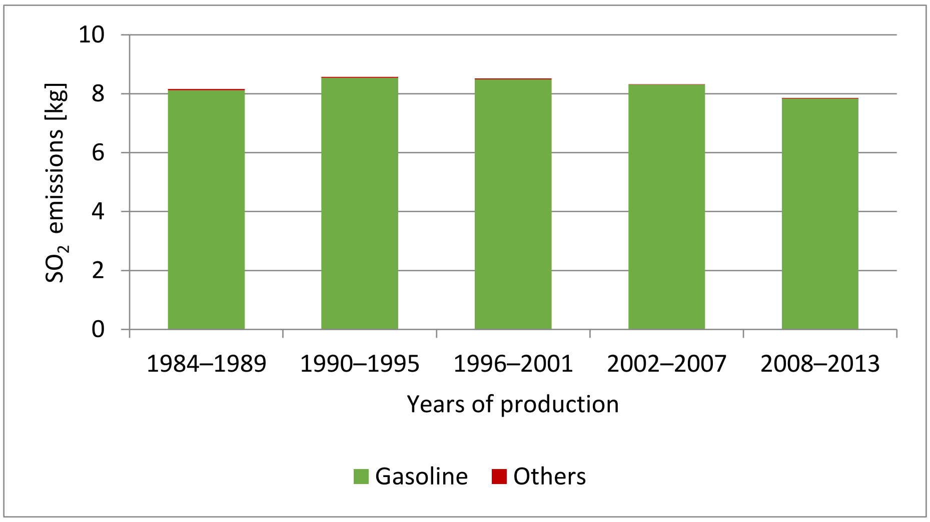

Figure 6. SO_2 emissions for the entire passenger car

The level of average SO_2 emissions in cars from subsequent production periods results in more than 99% of the fuel consumption. At the turn of the first and second period, SO_2 emissions increase by about 5%, and then systematically decrease, reaching the value of about 9% lower in vehicles from the last period.

3.5. Changes in energy inputs related to vehicle failure

The assessment of energy consumption in the operation phase of vehicles from different production periods takes into account the additional consumption of materials and energy resulting from the need to supply parts due to their unplanned, emergency wear. Average failure rates of basic vehicle combinations with mileage of 0-50 thousand kilometers km, 50-100 thous. km, 100–150 thous. km from the 1996–2001 and 2002–2007 production periods were determined on the basis of published Dekra reports. The process of producing new parts and product recycling were considered as sources of supply with parts needed for repair. The maximum energy input, based on the assumption that the entire unit or system is to be replaced, is summarized in tables 7 and 8.

Table 7. Energy inputs in [MJ] related to the failure rate of units for new parts in a passenger car depending on its mileage and production period

Production period		**1996–2001**			**2002–2007**	
Mileage [thousand km]	**0–50**	**50–100**	**100–150**	**0–50**	**50–100**	**100–150**
Electrics, electronics, lighting	457	1292	2134	493	1245	2103
Body, chassis, passenger compartment	289	695	1195	309	684	1239
Engine, exhaust system	308	1053	1879	546	1285	1949
Braking system	48	132	191	72	160	232
Driving system, steering system	327	1152	1876	220	702	1244
In total	1429	4324	7275	1640	4076	6767

Table 8. Energy inputs in [MJ] related to the failure rate of units for remanufactured parts in a passenger car depending on its mileage and production period

Years of production	**1996–2001**			**2002–2007**		
Mileage [thousand km]	**0–50**	**50–100**	**100–150**	**0–50**	**50–100**	**100–150**
Electrics, electronics, lighting	416	1189	1984	459	1145	1935
Body, chassis, passenger compartment	225	535	944	235	527	929
Engine, exhaust system	259	874	1541	464	1080	1617
Braking system	41	115	168	62	139	200
Driving system, steering system	271	968	1539	179	569	1020
In total	1212	3681	6176	1399	3460	5701

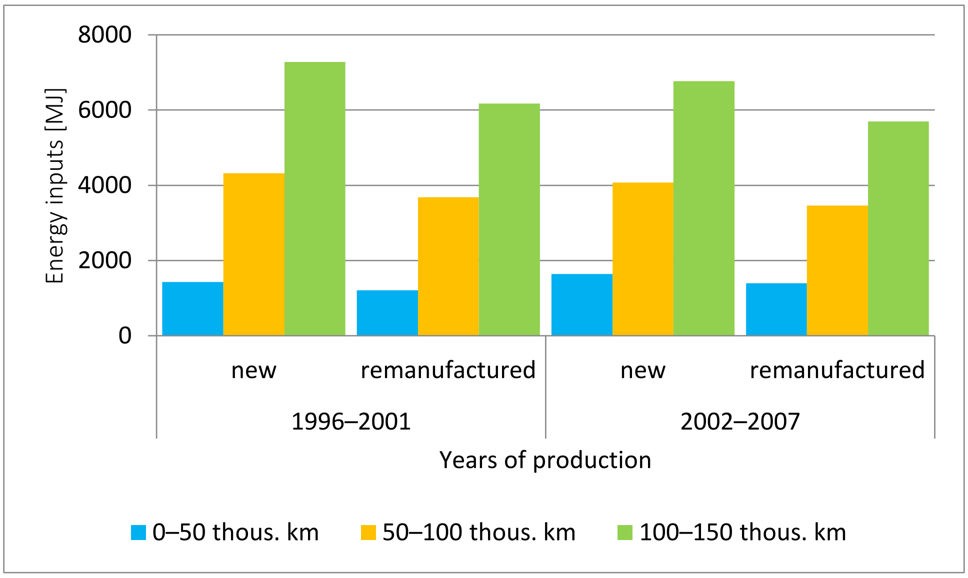

Figure 7. Energy expenditure related to the failure rate of units for new and remanufactured parts in a passenger car depending on its mileage and production period

Operation of older vehicles with mileage over 50,000 km, characterized by a higher failure rate, is associated with increased energy inputs per part (on average by about 6–8%), regardless of their source. At the same time, an increase in inputs by about 15% can be observed for newer vehicles with a mileage of up to 50,000 km. In the case of vehicles manufactured in the years 1996–2001, energy inputs related to emergency repairs, for which brand new parts are used, may constitute from about 23% to about 116% of the expenditure incurred for the failure-free annual operation of such a vehicle. For newer vehicles from 2002–2007, the maximum energy inputs are slightly lower, amounting to around 111%. The use of remanufactured parts makes it possible to reduce the maximum investment to about 98%, regardless of the age of the vehicle.

Conclusions

On the basis of the conducted research and their analysis, it can be unequivocally stated that from the point of view of the impact of a car on the environment throughout its life cycle, the most important role is played by the operating phase. The results of the analysis of environmental loads for the one-year operation period show that in the assessment of energy inputs and related emissions throughout the life cycle of a passenger car, the mileage of the car, determined both by the periodicity of replacement of elements and materials subject to normal wear and the duration of the assumed service life, is of crucial importance. It was also purposeful to take into account the additional loads related to the car's failure rate, which were related to the mileage of the passenger car expressed in thousands of kilometers traveled during the year. With the assumed average annual mileage of 15 thousand. km, the failure rate of the car was related to the average period of its operation, which was assumed to be equal to 6 years. However, the current impact assessment based solely on fuel consumption emissions may not be sufficient. Due to the significant role of the operation phase, a modern approach also requires taking into account the impacts related to scheduled periodic maintenance and removal of failures arising during use. The research results presented in the article show that this impact systematically increases along with the mileage of the car. Further limitations should be seen in the rationalization of repair processes (use of remanufactured parts for repairs, repair of components rather than their replacement) and, possibly, in improving the reliability of vehicles.

References

1. ISO 14040, 2006. *Environmental Management. Life Cycle Assessment*. Principles and Framework (Geneva, Switzerland).
2. ISO 14044, 2006. *Environmental Management. Life Cycle Assessment*. Requirements and Guidelines (Geneva, Switzerland).
3. Braess, H.-H., Finkenauer, W., Hamm, L., Rotberg, B.V., Weber, R., Willeke, R., Bellmann, K. *Lebensdauer, Recycling, Ressourcenschonung, Entwicklungstrends - Grundlagen und Probleme bei der Konzipierung gesamtwirtschaftlich optimaler Personenkraftwagen, Entwicklungslinien in der Kraftfahrzeugtechnik*. Proceedings of the 4. Statusseminar Kraftfahrzeug- und Straßenverkehrstechnik des Bundesministeriums für Forschung und Technologie (BMFT), 2. Jahrestagung der VDI-Gesellschaft Fahrzeugtechnik, Gemeinschaftsveranstaltung anl€aßlich des 75jahrigen Bestehens des Instituts für Landverkehrsmittel der Technischen Universitat Berlin vom 10.-12.11.1976 in Berlin. Verlag TÜV Rheinland.
4. Suzuki, T., Odai, T., Hukui, R., Takahashi, J. *LCA of Passenger Vehicles Lightened by Recyclable Carbon Fiber Reinforced Plastics*. Proceedings of the International Conference on Life Cycle Assessment, San Jose, Costa Rica. April 25-28, 2008.
5. Mayyas, A., Qattawi, A., Omara, M., Shan, D. *Design for sustainability in automotive industry: a comprehensive review*. Renew. Sustain. Energy Rev. **2012**, *16(4)*, 1845-1862. http://dx.doi.org/10.1016/j.rser.2012.01.012
6. Ballester, F. Air pollution and health: An overview with some case studies. In *Environmental health impacts of transport and mobility*, Nicolopoulou-Stamati, P., Hens, L., Howard, C.V., Eds.; Springer Netherlands, 2005, Volume 21, pp. 53–77.
7. Roussou, T., Behrakis, P. The Respiratory Effects of Air Pollution. In *Environmental health impacts of transport and mobility*, Nicolopoulou-Stamati, P., Hens, L., Howard, C.V., Eds.; Springer Netherlands, 2005, Volume 21, pp. 79–94.
8. Hensher, D.A., Button, K.J. *Handbook of transport and the environment*. Publisher Elsevier Science, Amsterdam 2003.
9. Raugei, M., Morrey, D., Hutchinson, A., Winfield, P. *A coherent life cycle assessment of a range of lightweighting strategies for compact vehicles*. J. Clean. Prod. **2015**, *108*, 1168-1176. http://dx.doi.org/10.1016/j.jclepro.2015.05.100

10. Regulation No 100 of the Economic Commission for Europe of the United Nations (UNECE) — Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train [2015/505]
11. World Business Council for Sustainable Development (WBCSD), 2004. Mobility 2030: meeting the Challenges to Sustainability. World Business Council for Sustainable Development, Conches-Geneva 2004.
12. Messagie, M.; Boureima, F.S.; Coosemans, T.; Macharis, C.; Mierlo, J. *Van A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels*. Energies **2014**, *7*, 1467–1482.
13. Zackrisson, M., Avellan, L., Orlenius, J. *Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues*. J. Clean. Prod. **2010**, *18(15)*, 1519–1529.
14. Gao, L.; Winfield, Z.C. *Life Cycle Assessment of Environmental and Economic Impacts of Advanced Vehicles*. Energies **2012**, *5*, 605-620, https://doi.org/10.3390/en5030605
15. Xiong, S.; Ji, J.; Ma, X. *Comparative Life Cycle Energy and GHG Emission Analysis for BEVs and PhEVs: A Case Study in China*. Energies **2019**, *12*, 834. https://doi.org/10.3390/en12050834
16. Van den Bossche, P., Vergels, F., VanMierlo, J., Matheys, J., Van Autenboer, W. *SUBAT: An assessment of sustainable battery technology*. J Power Sources **2006,** *162(2),* 913–919
17. Messagie, M.; Boureima, F.S., Matheys J. *Environmental performance of a battery electric vehicle: A descriptive Life Cycle Assessment approach*. World Electr. Veh. J. **2011**, *4(1)*, 782-786, DOI: 10.3390/wevj4040782
18. Ellingsen, L.A.-W., Majeau-Bettez, G., Singh, B. *Life cycle assessment of a lithium-ion battery vehicle pack*. J Ind Ecol **2014**, *18*, 113–124, https://doi.org/10.1111/jiec.12072
19. Faria R, Marques, P., Moura, P., Freire, F., Delgado, J., de Almeida A.T. *Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles*. Renew. Sust. Energ. Rev **2013**, *24*, 271–287, https://doi.org/10.1016/j.rser.2013.03.063
20. Bartolozzi, I., Rizzi, F., Frey, M. *Comparison between hydrogen and electric vehicles by life cycle assessment: a case study in Tuscany*. Appl. Energy **2013**, *101*, 103–111, https://doi.org/10.1016/j.apenergy.2012.03.021
21. Donateo, T., Ingrosso, F., Lacandia, F., Pagliara, E. *Impact of hybrid and electric mobility in a medium sized historic city*. SAE Technical Paper 2013–24 –0077.EC-JRC, DOI: https://doi.org/10.4271/2013-24-0077
22. Casals, L.C., Martinez-Laserna, E., García, B.A., Nieto, N. *Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction*. J. Clean. Prod. **2016**, *127*, 425–437, https://doi.org/10.1016/j.jclepro.2016.03.120
23. Bauer, C., Hofer, J., Althaus H-J., Del Duce, A., Simons, A. *The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework*. Appl. Energy **2015**, *157*, 871–883, https://doi.org/10.1016/j.apenergy.2015.01.019
24. Hawkins, T.R., Gausen, O.M., Stromman, A.H. *Environmental impacts of hybrid and electric vehicles—a review*. Int J Life Cycle Assess. **2012**, *17(8)*, 997–1014.
25. Lombardi, L., Tribioli, L., Cozzolino, R., Bell, G. *Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrain based on LCA*. Int J Life Cycle Assess. **2017**, *22*, 1989–2006
26. Harris, A.; Soban, D.; Smyth, B.M; Best, R. *Assessing life cycle impacts and the risk and uncertainty of alternative bus technologies*. Renew. Sust. Energ. Rev. **2018**, *97*, 569-579. DOI: 10.1016/j.rser.2018.08.045
27. Eberle, R. *Dissertation zum Thema „Methodik zur ganzheitlichen Bilanzierung im Automobilbau"*. Technische Universität Berlin, Fakultät 10, Berlin 2000.
28. Corradini, R., Hutter, C., Köhler, D. *Ganzheitliche Bilanzierung von Grundstoffen und Halbzeugen.* Forschungstelle für Energiewirtschaft e.V., Munich 1999.