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Comparative Assessment of Materials Used in the Construction of Passenger Cars in Terms of Energy Demand and Harmful Emission

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Abstract:

Purpose: *The article refers to the current energy and ecological issues related to the life cycle assessment of vehicles. The main objective of the study was to compare the environmental impact of changes in passenger car design with the use of the Life Cycle Analysis (LCA). LCA is now a widely used decision-making tool in the automotive industry to improve the energy and environmental performance of new cars.*
Design/Methodology/Approach: *A simplified LCA method, which, in strictly defined cases, can be used to analyse the environmental impacts related to the manufacturing process of a passenger car, has been presented in the paper. Environmental inputs such as energy, required to provide materials and CO_2 and SO_2 emissions were used to evaluate the impact. The values of these variables were identified based on the material mass used to build the car.*
Findings: *The environmental burdens resulting from the use of individual types of materials in the most important functional units of the car were compared. Both the energy inputs and the environmental burdens increased at the turn of the analysed periods.*
Practical implications: *The results of the analysis allowed to identify the materials with the greatest environmental impact.*
Originality/value: *A life cycle model of a passenger vehicle with a conventional drive that allows to determine its environmental burdens was created.*

Keywords: *Environment pollution, passenger car, life cycle assessment (LCA).*

JEL code: *O33, Q30.*

Paper Type: *Research article.*

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1. Introduction

The growing number of produced and used cars causes that the issue of the global consumption of natural resources and the management of waste generated during operation and after end-of-life vehicles, remains unresolved. According to estimates, transport is responsible for 22% of man-made CO_2 emissions (UNECE, 2021). Most of this comes from passenger vehicles which contribute to 45% of global transport CO_2 emissions (International Energy Agency, 2022). Cars emit 40% of nitrogen oxides into the air (European Environment Agency, 2021).

Over 80% of urban residents are exposed to air pollution exceeding the standards set by the World Health Organization (WBCSD, 2021). On the other hand, end-of-life vehicles are responsible for 40 million tons of waste in the world every year (Sakai *et al.*, 2014).

Over the years we have been observing changes in the material composition of vehicles (Merkisz-Guranowska, 2018; Sullivan *et al.*, 2015). These changes are forced by the necessity to reduce the weight of the vehicle in order to reduce fuel consumption and CO_2 emissions, improve safety and comfort of traveling, and reduce production costs by replacing more expensive materials with cheaper ones.

New materials introduced in the construction of vehicles, which have a direct impact on their weight, fuel consumption and safety, are a huge progress in the automotive industry, both in the construction of bodies, chassis and drive units. The result is the use of increasingly light, highly durable, easily processed and corrosion-resistant materials, such as modern aluminum alloys or plastics and composites, which replace the previously used high-quality steels or iron castings.

Despite the development of various types of materials, metal alloys are still the most widely used in the automotive industry and make up 60% to 70% of the weight of the vehicle. New solutions for the construction of cars made of aluminum and plastic materials reduce the weight of the vehicle, and thus reduce its harmful effects by reducing, first of all, fuel consumption and emissions of harmful substances to the environment (Merkisz-Guranowska, 2020; Kadlubek *et al.*, 2022).

However, some changes in the material structure may increase the negative impact, e.g., by releasing harmful gases. Another consequence of changes in the material structure is the demand for energy for the production of materials used in the construction of vehicles. Some of the materials will be reused as a result of material recycling. Legal regulations in the European Union, Great Britain and Norway oblige to recover 95% of the weight of end-of-life vehicles. The benefits of using raw materials for material recycling translate into the demand for energy necessary to produce new vehicles.

The article presents selected aspects of the methodology for determining the levels of energy consumption and emissivity related to material and technological inputs occurring in the vehicle production phase.

2. Methodology of Car Energy Consumption and Emissivity Assessment

Nowadays the energy and ecological assessment of a car already at the construction stage is one of the most essential indicators influencing both the quality and competitiveness of a given vehicle on global markets. One of the most effective methods for quantifying a car's environmental impact is the Life Cycle Assessment (LCA). It is used to determine the potential environmental impact of processes related to the entire lifetime of a car, from the production of materials, through the production of the car, its use, and end-of-life management.

There are many studies that evaluate a car in terms of its life cycle. The method is used to assess the impact of whole vehicles (Del Pero *et al.*, 2018), individual elements or subassemblies (Peters, 2016), production technology (Papasavva, 2005) or the materials used in car construction. The results of this assessment make it possible to modify the structure of the car in order to minimize its impact on the environment. A review of publications relating to the use of LCA methods to assess the environmental impact of vehicles and components has been included in (Mrozik and Merkisz-Guranowska, 2021).

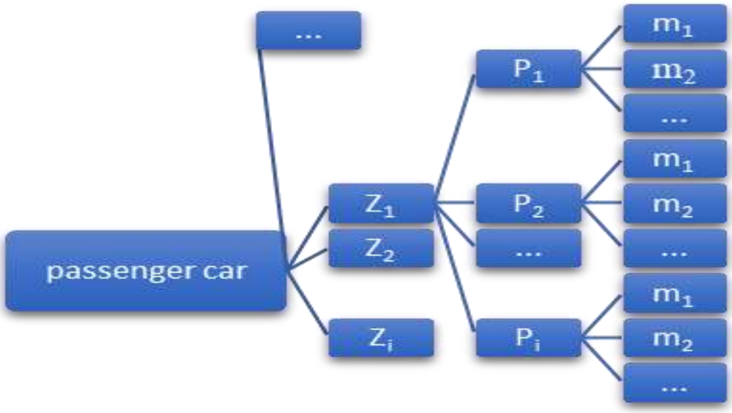
The article presents the energy and ecological comparative assessment of the structures and materials used in the construction of passenger cars on the basis of the life cycle model of the passenger vehicle, with the use of LCA data according to the requirements of ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14040, 2006).

In line with the aim of the research, in order to effectively compare the environmental profiles of cars in the long term, the scope of the assessment was limited to the processes and material streams directly related to the production of materials. However, the impact of production and the infrastructure of transport was not taken into account. This means that substances that are released to the environment exceed system boundaries covering the entire life cycle only during these processes (the phases of the car production, use and recycling).

The primary objective of the discussed method is the analysis method model of the vehicle structure presented in Figure 1. In the first stage the passenger car is divided into assemblies (Z). Later division into subassemblies (P) that consist of individual materials (M) with a certain mass (m) can be observed.

After conducting a detailed inventory, materials are divided into four fundamental groups, ferrous metals, aluminum and its alloys, plastics and rubber, and other materials.

Figure 1. *Analysis model of passenger vehicle decomposition*



Source: *Own study.*

The key issue in determining the energy and emission outlays for specific types of materials is to identify the material structure of a vehicle. After the material decomposition of the vehicle has been carried out, it is possible to create mass balance equations in accordance with the mathematical notation given below. The weight of the car can be calculated as the sum of the masses (*m*) of all materials used to build the vehicle.

On the other hand, the size of individual material inputs can be calculated using the general relationships given below, reflecting the summation of the amount of a given type of material in individual components and subassemblies of the vehicle.

The basis for the analysis of energy consumption and emissivity for the construction phase of passenger cars – referred in the case under consideration only to material inputs - is to determine the total weight of individual materials that make up a given vehicle immediately after its production in the manufacturer's assembly plant and the unit values of energy inputs (*ne*) as well as the specific emissions (*em*) for a given type of material.

The analysis of the environmental impact of the production phase was performed for 33 vehicles of the B and C segments, produced by various manufacturers in 1990, 2000 and 2010 and with comparable operational characteristics. These were hatchback (3 and 5-door) and sedan (4-door) cars, with a 1.2-1.5 dm^3 gasoline engine, manual gearbox, front-wheel drive and basic equipment of the following brands: Volkswagen, Ford, Opel, Toyota, Renault, Peugeot, Citroën and Fiat.

In the analyzed time periods, subsequent vehicles of a given brand were the successors of the earlier model, e.g. the VW Golf 5-door with a 1.2 dm^3 gasoline engine produced in 2010 was a newer version of the VW Golf 5-door with an engine of the same capacity produced in 2000 and an earlier model from 1990.

Thanks to this choice, it was possible, inter alia, to carry out a detailed comparison study of the environmental loads for vehicles of different manufacturers, taking into account their changes in the material structure of vehicles in the period under consideration, as well as the possibility assessment of pro-ecological rationalization of car production in the future. Data on materials (materials footprints) from 1990, 2000 and 2010, respectively, were used to calculate the environmental loads of vehicles.

The high complexity of the structure and the lack of detailed data on the production processes meant that the energy and ecological characteristics of the discussed vehicles were established on the basis of the results of a detailed material inventory with known properties used for their production.

Data on the material composition was acquired during tests conducted at a certified dismantling plant in Szczecin (Poland). In order to make a list of materials used in production, the cars were disassembled into assemblies and individual parts. After the parts were weighed, it was possible to determine what kind of material was used. For many small parts, it was one material and a similar technology. In this case, the total weight of the parts listed is given in kg.

The database of the vehicle manufacturer IDIS made it possible to complete the missing material data for some car components, such as plastic and rubber body parts. Thorough analysis allowed to distinguish 27 material groups. Their combined environmental burdens in relation to energy intensity and emissions accounted for 95% of the environmental impact value of the total mass of raw materials that contributed to the vehicle production process (e.g. Steel, cast steel, cast iron, aluminum and its alloys and petrol).

The environmental analysis of selected material groups was made on the basis of the characteristics contained in the available databases: Gemis and LCA Plastics Europe Report and auxiliary computational programs: SimaPro and Greet.

3. Results and Environmental Loads Assessment

Table 1 shows the results of the analysis of the material composition of the analyzed vehicles divided into four main groups.

Due to the fulfilled conditions of the normality of the distribution of variables and the homogeneity of variance, the ANOVA analysis of variance (independent samples) was used to check the significance of changes in the material structure, energy expenditure as well as CO_2 and SO_2 emissions in three periods (1990, 2000 and 2010). Tukey's test was used as a post-hoc test to thoroughly investigate which pairs of periods there are significant differences between. A value of $p<0.05$ was considered statistically significant. The calculations were statistically performed with the use of the STATISTICA 10 PL statistical package.

ANOVA analysis showed significant differences in the level of percentages for steel, cast steel and cast iron, aluminum and its alloys as well as plastics and rubber between the analyzed periods. The percentage share of steel, cast steel and cast iron decreased in the following years. It was the highest in 1990 and the lowest in 2010. In turn, the percentage share of aluminum and its alloys as well as plastics and rubber increased in the following years. It was the lowest in 1990 and the highest in 2010.

On the basis of these changes, a study of energy intensity and emissivity was carried out in relation to the given environmental impact categories. The characteristics received were determined for the whole vehicle and illustrated the changes in the magnitude of the generated environmental loads.

Table 1. *Mean values with standard deviations of the percentages of selected materials in the years 1990-2010 and the results of ANOVA and Tukey's test*

Material	Year	n	Share [%]		ANOVA		p level - Tukey's test		
			Mean value	Std deviation	F	p	1990 vs. 2000	1990 vs. 2010	2000 vs. 2010
Steel, cast steel, cast iron	1990	11	65.5%	2.2%	26.94	<0.0001	0.0003	0.0001	0.0302
	2000	13	62.7%	1.0%					
	2010	9	60.9%	0.7%					
Aluminum and its alloys	1990	11	6.7%	0.4%	39.98	<0.0001	0.0002	0.0001	0.0009
	2000	13	7.4%	0.2%					
	2010	9	7.9%	0.3%					
Plastics and rubber	1990	11	12.0%	1.0%	57.70	<0.0001	0.0001	0.0001	0.0217
	2000	13	14.2%	0.6%					
	2010	9	15.0%	0.2%					

Source: *Authors' calculations.*

A statistically significant level of $p<0.05$ is marked in red, n - number of vehicles, F - value of the F statistics, p - probability level.

Analogously to the assessment of changes in the material composition, the ANOVA analysis of variance was used to check the significance of the difference in the level of energy outlays, CO_2 emissions and SO_2 emissions in the three analyzed periods. Tukey's test was used to investigate between which pairs of periods there are significant differences. A value $p<0.05$ was considered statistically significant.

Table 2. *Average energy expenditure in MJ with standard deviations for selected materials in 1990-2010 and the results of ANOVA and Tukey's test*

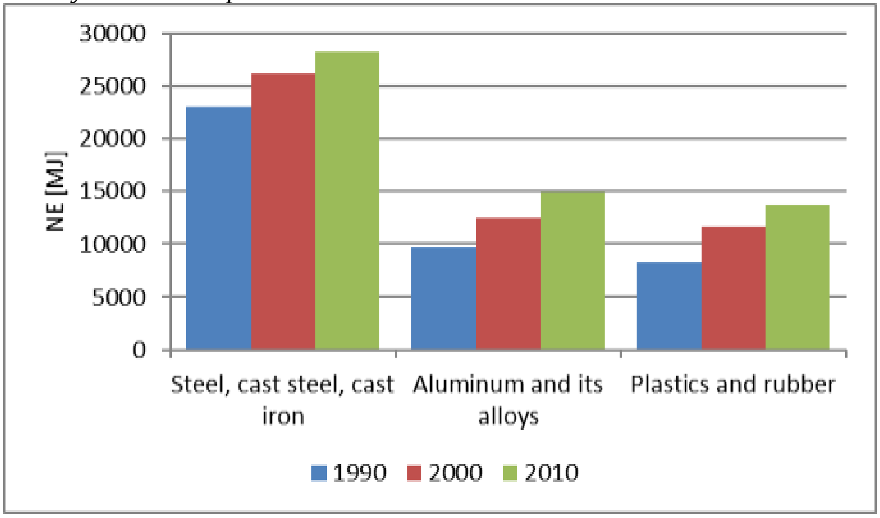
Material	Year	n	NE [MJ]		ANOVA		p level - Tukey's test		
			Mean value	Std deviation	F	p	1990 vs. 2000	1990 vs. 2010	2000 vs. 2010

Steel, cast steel, cast iron	1990	11	23109.3	2068.6	10.86	0.0003	0.0191	0.0005	0.2021
	2000	13	26229.4	2576.3					
	2010	9	28325.7	2961.3					
Aluminum and its alloys	1990	11	9722.4	1449.0	31.43	<0.0001	0.0004	0.0001	0.0044
	2000	13	12529.6	1516.0					
	2010	9	14955.3	1453.0					
Plastics and rubber	1990	11	8323.7	1544.9	26.49	<0.0001	0.0003	0.0001	0.0359
	2000	13	11617.3	1736.6					
	2010	9	13679.4	1725.8					

Source: *Authors' calculations.*

ANOVA analysis (Table 2) showed significant differences in the level of energy inputs between the studied periods for steel, cast steel and cast iron, aluminum and its alloys, as well as plastics and rubber. Energy expenditures for selected materials increased in the following years. They were the lowest in 1990 and the highest in 2010.

Figure 2. *Average energy expenditure of steel, cast steel and cast iron, aluminum and its alloys as well as plastics and rubber in 1990-2010*



Source: *Authors' calculations.*

Table 3 shows the average CO_2 emissions, and Table 4 shows SO_2 for the tested materials.

The situation with CO_2 and SO_2 emissions is similar to the energy inputs. The ANOVA analysis showed significant differences in the level of CO_2 emissions and SO_2 emissions between the studied periods, both for steel, cast steel and cast iron, as well as for aluminum and its alloys, and for plastics and rubber. CO_2 emission and SO_2 emission increased for selected materials in the following years. The lowest emissions were in 1990 and the highest in 2010.

Table 3. *Average CO_2 emissions in kg with standard deviations for selected materials in 1990-2010 and the results of ANOVA and Tukey's test*

Material	Year	n	CO_2 [kg]		ANOVA		p level - Tukey's test		
			Mean value	Std deviation	F	p	1990 vs. 2000	1990 vs. 2010	2000 vs. 2010
Steel, cast steel, cast iron	1990	11	2592.1	232.0	10.86	0.0003	0.0191	0.0005	0.2021
	2000	13	2942.1	289.0					
	2010	9	3177.2	332.2					
Aluminum and its alloys	1990	11	618.7	92.2	31.43	<0.0001	0.0004	0.0001	0.0044
	2000	13	797.3	96.5					
	2010	9	951.7	92.5					
Plastics and rubber	1990	11	392.8	64.8	34.25	<0.0001	0.0001	0.0001	0.0211
	2000	13	550.7	75.4					
	2010	9	643.5	64.3					

Source: *Authors' calculations.*

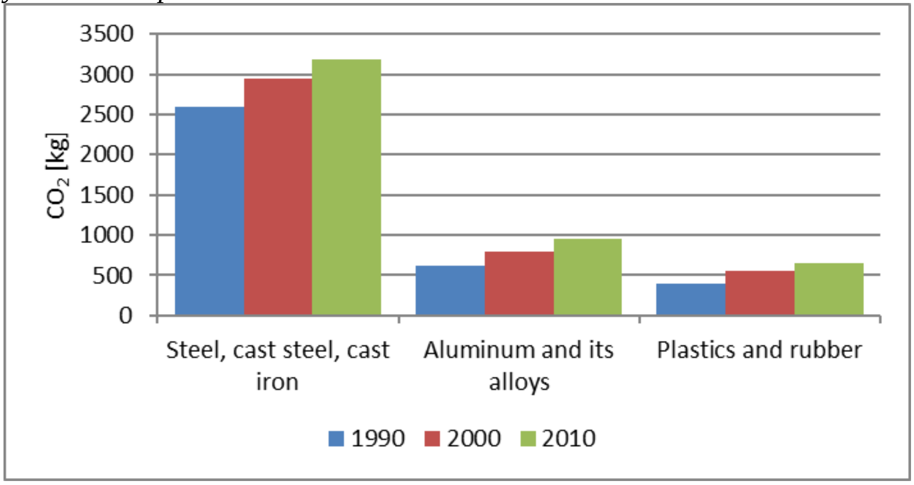
Table 4. *Average SO_2 emissions in kg with standard deviations for selected materials in 1990-2010 and the results of ANOVA and Tukey's test*

Material	Year	n	SO_2 [kg]		ANOVA		p level - Tukey's test		
			Mean value	Std deviation	F	p	1990 vs. 2000	1990 vs. 2010	2000 vs. 2010
Steel, cast steel, cast iron	1990	11	1.12	0.10	10.86	0.0003	0.0191	0.0005	0.2021
	2000	13	1.27	0.13					
	2010	9	1.38	0.14					
Aluminum and its alloys	1990	11	2.01	0.30	31.43	<0.0001	0.0004	0.0001	0.0044
	2000	13	2.59	0.31					
	2010	9	3.09	0.30					
Plastics and rubber	1990	11	0.60	0.10	31.94	<0.0001	0.0002	0.0001	0.0195
	2000	13	0.83	0.11					
	2010	9	0.98	0.11					

Source: *Authors' calculations.*

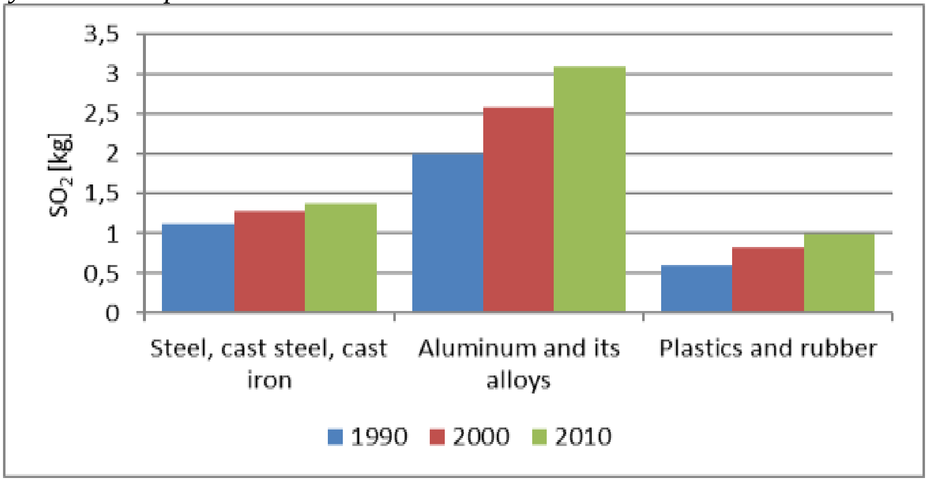
The comparison of the levels of energy inputs with the division into individual materials (Figure 2) shows that the difference in these levels in cars of different generations increases with time. It can also be seen that the energy required to produce materials in subsequent models of passenger cars increases faster than the weight of the car. This means that each of the components of this mass has a different influence on this tendency of changes in energy inputs. The level of energy inputs is related mainly to the weight of steel, cast steel and cast iron.

Figure 3. *Average CO_2 emissions of steel, cast steel and cast iron, aluminum and its alloys as well as plastics and rubber in 1990-2010*



Source: *Authors' calculations.*

Figure 4. *Average SO_2 emissions of steel, cast steel and cast iron, aluminum and its alloys as well as plastics and rubber in 1990-2010*



Source: *Authors' calculations.*

The greatest impact on the increase in the total energy demand for car production is the increase in the weight of other materials, such as aluminum and its alloys, as well as plastics and rubber. The effect of such changes is a systematic increase in the share of these materials in the total level of energy inputs of the car, while reducing the share of steel, cast steel and cast iron. However, the share of steel, cast steel and cast iron still accounts for about half of the total energy input.

The impact of steel, cast steel and cast iron is also the largest in the category of CO_2 emissions (Figure 3) and SO_2 emissions (Figure 4). These emissions also show an upward trend.

4. Conclusions

The basic model assumptions presented in the above article constitute a new approach to the issues related to the determination of cumulative energy inputs and cumulative emission levels occurring in the construction phase of passenger vehicles.

For steel, cast steel and cast iron, energy inputs, CO_2 emissions and SO_2 emissions in 2000 were on average higher by about 13.5% compared to 1990, and in 2010 they were higher by an average of about 22.6% compared to 1990 and were higher on average by about 8.0% compared to 2000.

For aluminum and its alloys, energy inputs, CO_2 emissions and SO_2 emissions in 2000 were higher by an average of about 28.9% compared to 1990, and in 2010 they were higher by an average of about 53.8% compared to 1990 and were higher on average by about 19.4% compared to 2000.

For plastics and rubber energy inputs in 2000 were higher on average by about 39.6% compared to 1990, and in 2010 they were higher by an average of about 64.3% compared to 1990 and were higher by an average of about 17.7% compared to year 2000. CO_2 emissions in 2000 were higher on average by approx. 40.2% compared to 1990, and in 2010 they were higher by approx. 63.8% on average compared to 1990 and were higher by approx. 16.8% on average compared to year 2000. SO_2 emission in 2000 was higher on average by about 39.5% compared to 1990, and in 2010 it was higher by an average of about 64.3% compared to 1990 and was higher by an average of about 17.8% compared to year 2000.

The results of comparing the environmental impact of passenger cars from different production periods clearly show that the potential for environmental pollution during the production phase of a passenger car shows an increasing trend. This is due to the increasing weight of the car, which increased on average by over 40% between 1990 and 2010.

The increase in weight is closely related to the materials used. In the period covered by the research, user expectations, as well as safety and environmental standards have changed radically. The effect of the changes in the design and equipment of vehicles and the increasing pressure to reduce energy demand in transport is the increasing use of lightweight materials. This can be interpreted as a manifestation of continuous improvement of car design and pressure to reduce environmental burdens during the operation phase.

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