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Material-energy model of motor vehicle life cycle

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Preliminary note

Nowadays one of the most important elements of economic and social lives is motorization. Its development is most of all accompanied by increasing the use of various means of transport, especially motor vehicles. Such a significant increase in the amount of vehicles produced can be implemented by the global use of productive materials and energy carriers, which is increasingly higher each year. Operating a higher number of vehicles causes an increase in environment pollution, not only by deleterious substance emissions, being the effect of fuel combustion, or implementation of production processes in the automotive industry, but also by a growing amount of exchanged parts and sub-assemblies and, mostly, by the rapid growth of vehicles that are withdrawn from traffic and subjected to car breaking.

The article presents a material-energy model of a motor car life cycle that can be helpful in determining the type and size of the expenditure of material and energy as well as emission loading in particular phases and the whole life cycle of a vehicle. Based on the input data contained in [9] analysis of the results of calculations related to examples of the material structure of the model vehicle from 1990 and 2000 and the impact of these changes on energy consumption and emission levels were presented.

Keywords

life cycle assessment,
passenger car,
energy and environment management

Materijalno-energetski model životnog ciklusa motornog vozila *

Prethodno priopćenje

Jedan od najvažnijih elemenata ekonomskog i društvenog života u današnje vrijeme je motorizacija. Njen razvoj je u najvećoj mjeri popraćen povećanim uporabom prijevoznih sredstava, posebice motornih vozila. Takvo značajno povećanje količine proizvedenih vozila provodi se zbog globalne uporabe proizvodnih materijala i nositelja energije iz godine u godinu je sve veća i veća. Veći broj vozila u pogonu povećava zagađenje okoliša, ne samo emisijama štetnih tvari u okoliš, koje su posljedica izgaranja goriva, ili izvođenje procesa proizvodnje u automobilskoj industriji, već i zbog porasta količine promjenljivih dijelova i podsklopova, a ponajviše zbog ubrzanog rasta broja vozila koja se povuku iz prometa i rastavljaju.

Članak predstavlja materijalno-energetski model životnog vijeka motornog vozila koji uvelike može pomoći prilikom određivanja vrste i veličine troškova materijala i energije, kao i ispuštanja emisija u određenim fazama i cjelokupnog životnog vijeka vozila. Na temelju ulaznih podataka koji se nalaze u [9] predstavljena je analiza rezultata proračuna koji se odnosi na primjere strukture materijala modela vozila od 1990. i 2000. i utjecaja na promjene u potrošnji energije i emisiji štetnih plinova.

Ključne riječi

metoda životnog ciklusa
osobna vozila
upravljanje energijom i okolišem

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1. Introduction

Industrial development of mankind and civilization of recent decades is accompanied by the increasing use of various means of transport, particularly cars. This movement each year is accompanied by a significant increase in the generation of cars that is achieved by increasing the global consumption of raw materials production, energy, and the need to build new vehicle assembly plants. The exploitation of an increasing number of vehicles powered by conventional and unconventional fuels is also related to, increasing at an accelerating rate, environmental pollution, not only by the emission of harmful substances resulting from fuel combustion or manufacturing processes in the automotive industry, but also by an increasing number of parts and components that need to be exchanged, and above all the rapidly growing number of vehicles out of service and undergoing the process of scrapping. Moreover, due to legal regulations in EU countries connected with the end of life of vehicles and dismantling centers [19, 20], the vehicle parts should be recycled.

As it can be seen, the concept of environmental protection and the ecology concept has existed in the automotive industry for decades. Given the increasing pace of technological progress in the world, the aspects of reduction in environmental pollution in the production, operation and decommissioning of the vehicle are very important. A perfect solution to this problem is the LCA method, which is used not only to perform the analysis of products produced in the automotive industry but can also be used in many industries.

Symbols/Oznake

MI	- material inputs - ulazni podaci o materijalu	ei_i	- individual energy inputs for the particular material, MJ/kg - pojedinačni ulazni podaci o energiji za svaki određeni materijal, MJ/kg
EI	- energy inputs - ulazni podaci o energiji	em_{i/CO_2}	- individual emissions of CO_2 respectively for the particular material, kg/kg - pojedinačne emisije CO_2 koje se odnose na određeni materijal, kg/kg
EL	- environmental load - opterećenje okoliša	em_{i/SO_2}	- individual emissions of SO_2 respectively for the particular material, kg/kg - pojedinačne emisije SO_2 koje se odnose na određeni materijal, kg/kg
m	- mass of the vehicle, kg - masa vozila, kg	em_{i/NO_x}	- individual emissions of NO_x respectively for the particular material, kg/kg - pojedinačne emisije NO_x koje se odnose na određeni materijal, kg/kg
ei	- individual values of energy inputs, MJ - pojedinačne vrijednosti ulaznih podataka o energiji, MJ		**Subscripts/Indeksi**
em	- individual emissions, kg/kg - pojedinačne emisije, kg/kg	i	- materials - materijali
CEI	- cumulative energy inputs - kumulativni ulazni podaci o energiji	FB	- construction phase - faza izrade
$m_{i/FB}$	- mass of the particular material, kg - masa određenog materijala, kg		-

The first attempts to use Life Cycle Assessment (LCA) were taken in the 70s of the 20th century. This method was initiated at the same time in four different countries: Sweden, Great Britain, Switzerland and the United States of America [1]. One of the pioneers in this issue was Harold Smith who in 1963 at the World Energy Conference presented the results of research on the consequences of the production on the environment of various types of energy in some chemical processes. The analysis covered the period of life of the process from the extraction of raw materials to the final product [6,7]. In the following years there were more similar reports; it was the effect of the rising energy crisis. At that time, modeling methods were quite simple and they focused mainly on the analysis of energy consumption and the final waste production. The objects of that analysis were mainly household products such as beverage containers. The LCA notion appeared in the 80's. It was then that the need to define the functional unit that allows comparisons of different products appeared [1]. In the 90s of the 20th century, the International Standards Organization (ISO) developed the first ISO 14040 series of standards on life cycle assessment (LCA). Initially, four standards were created: 14040, 14041, 14042 and 14043, which in 2006 were revised and consolidated into two: 14040 and 14044 [1,2,3]. The authors of the first works, devoted to aspects of life cycle analysis of vehicles formed in the second half of 1970s of the last century, were H.-H. Braess, L. Hamm and W. Finkenauer [5,6,7], who should be regarded as the pioneers of this subject. This topic was continued in the 90s of the last century and the first years of this century, i.e. by M. Schuckert, R. Eberle, M. Delluchi, Sullivan, J. L. and Kobayashi, O. [8,9,10,12,13,14]. In the 90s last century, great attention was paid to the energy input needed to produce a vehicle, which was manifested in the works f.e. Sullivan, J. L., et. al. Kobayashi, O., Maclean, H.L., et. al. [12,13,14,15]. Works published in recent years are devoted to the input of materials and energy necessary to produce the vehicle and its impact on the environment [16,17,18]. In Poland, work related to energy and environmental life cycle assessment of vehicles has been carried out by the authors of this paper for two years [4].

2. Model Description

The model of material-economic analysis of the power technologies life cycle presented in the paper is based on the analysis of LCA according to the ISO 14040 and ISO 14044 standards. Life Cycle Assessment (LCA) is a technique that aims to assess the environmental risks associated with the product or process, either through the identification and quantification of waste materials and forms of energy or waste discharged into the environment, and assessment of the impact of these materials, energy and waste on the environment. The life cycle of a given technology is a concept known since the 70s of the 20th century. In recent years, a continuous increase in the demand for fuel and raw materials production can be observed. This is connected primarily with the increase in the number of vehicles on the road. There are fewer and fewer natural resources and the requirements for theenvironmental protection for the whole area of vehicle technology are growing. This applies not only to fuel consumption and spare parts, but the whole process from production to the scrapping of the vehicle.

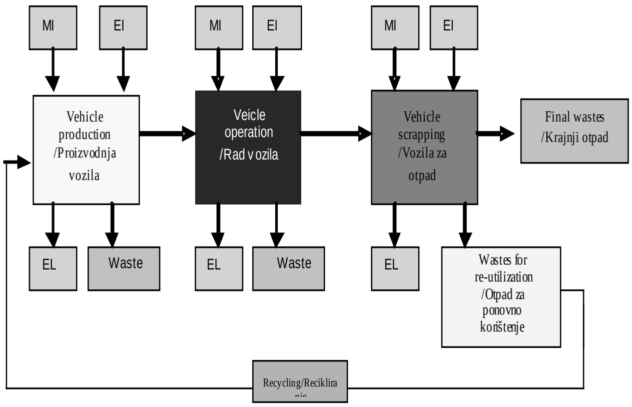

Figure 1. Block diagram of the vehicle life cycle

Slika 1. Blok shema životnog vijek vozila

Figure 1 shows the block diagram of the life cycle of the vehicle where: MI is material inputs, EI- energy inputs and EL – environmental load.

The model shown in Fig. 1 consists of the following areas:

- I area – vehicle production;
- II area – vehicle operation;
- III area – vehicle scrapping.

The primary objective of the model is to provide an analysis of energy consumption and emission for the construction phase of cars, in this case related only to the material inputs. The first step in this method is the analysis of materials in which the basic assumptions are listed below.

The established methods of material analysis of a motor vehicle were presented in Figure 2 and include the divisions at the following levels of decomposition:

- the area of the vehicle assemblies (e.g., car body, chassis, etc),
- the area of the vehicle components (e.g. body, windows, etc.) and
- the area of the materials (e.g. high-alloy steel, aluminum, rubber, plastic materials, etc.) which is the lowest level of the vehicle decomposition.

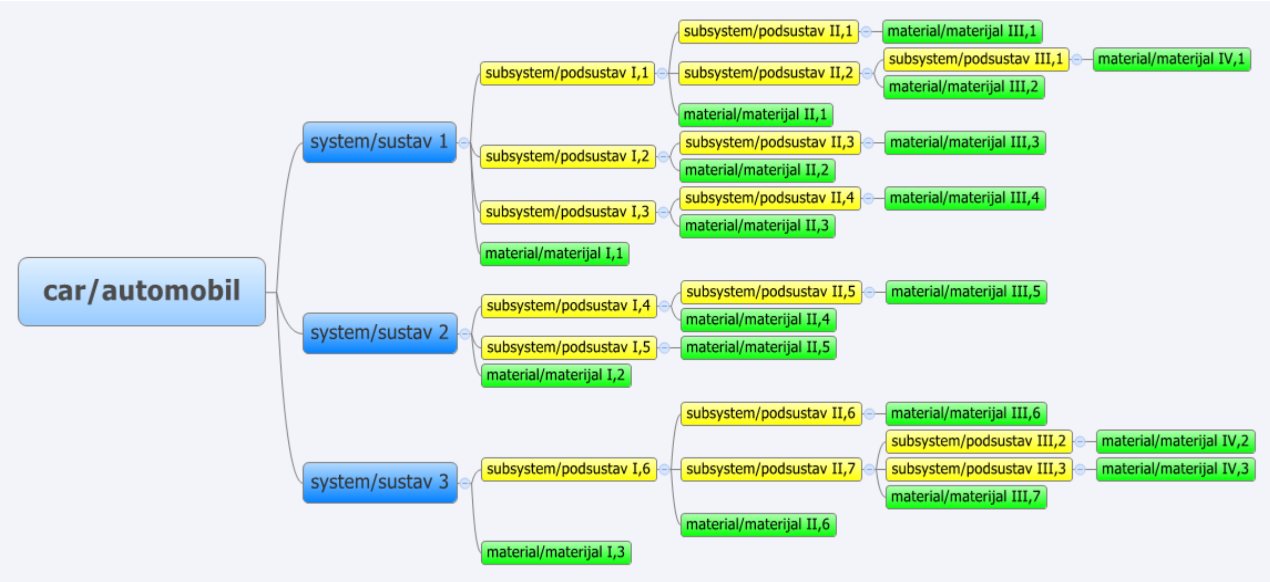

Figure 2. Motor vehicle decomposition

Slika 2. Rastavljanje motornih vozila

After the decomposition of materials, it is possible to create a mass balance equation according to the mathematical writing given below. The mass of the vehicle can be calculated as the sum of the masses of all the materials used:

$$m = m_1 + m_2 + m_3 + \ldots + m_I \ , \tag{1}$$

$$m = \sum_{i=1}^{I} m_i \ . \tag{2}$$

The levels of decomposition were determined with Greek numerals. The mass of the material, occurring within each level of decomposition of the vehicle, can be determined according to the following relationships:

$$m_{1,1} = m_{1,1,1} + m_{1,1,2} + m_{1,1,3} + \ldots + m_{1,1,K} \ , \tag{3}$$

$$m_{1,1} = \sum_{k=1}^{K} m_{1,1,k} \ . \tag{4}$$

The total mass of the material appearing in all levels of decomposition of the vehicle can be determined by the following equations:

$$m_1 = m_{1,1} + m_{1,2} + m_{1,3} + \ldots + m_{1,N} \ , \tag{5}$$

$$m_1 = \sum_{n=1}^{N} m_{1,n} = \sum_{n=1}^{N} \sum_{k=1}^{K_n} m_{1,n,k} \ , \tag{6}$$

which in the end leads to the formula:

$$m = \sum_{i=1}^{I} \sum_{n=1}^{N} \sum_{k=1}^{K_n} m_{i,n,k} \tag{7}$$

3. Selected example of the materials structure

Table 1, based on data contained in [9], presents a comparison of the percentage of individual types of materials in the structure of a passenger car from 1990 and 2000. While on its basis, taking into account the average passenger vehicle mass at the level of 1200 kg, the consumption of individual materials in the construction phase for the sample car given above were obtained and presented in Table 2.

Table 1. Percentage of material in the structure for the example of the passenger car from 1990 and 2000 [9]

Tablica 1. Udio materijala u strukturi primjerka osobnog vozila iz 1990. i 2000. [9]

Percentage of the material /Udio materijala	1990	2000	Change/Promjena
steel, cast steel, cast iron [%]/čelik, lijevani čelik, lijevano željezo [%]	67	60	− 7
aluminum and its alloys [%]/aluminij i njegove legure [%]	5	7	+ 2
other non-ferrous metals (zinc, copper, magnesium) [%]/ostali neobojeni metali (cink, bakar, magnezij) [%]	3	3	0
plastic materials and rubber [%]/plastični materijali i guma[%]	10	15	+ 5
other materials (including consumables) [%]/ostali materijali (uključujući	15	15	0

potrošne materijale) [%]			

Table 2. Percentage material mass for the example of the passenger car from 1990 and 2000 [9]

Tablica 2. Udio mase materijala primjerka osobnog vozila iz 1990. i 2000. [9]

Material mass/Masa materijala	1990	2000	Change/Promjena
steel, cast steel, cast iron [kg]/ čelik, lijevani čelik, lijevano željezo [kg]	804	720	− 84
aluminum and its alloys [kg]/ aluminij i njegove legure [kg]	60	84	+ 24
other non-ferrous metals (zinc, copper, magnesium) [kg]/ ostali neobojeni metali (cink, bakar, magnezij) [kg]	36	36	0
plastic materials and rubber [kg]/ plastični materijali i guma[kg]	120	180	+ 60
other materials (including consumables) [%]/ostali materijali (uključujući potrošne materijale) [kg]	180	180	0

Tables 1 and 2 show that the main materials that are used to build vehicles include: carbon and high alloy steels and materials from cast iron and cast steel (such as forgings, castings), light metals (mainly aluminum alloys), other non-ferrous metals (e.g. zinc, copper, magnesium, etc.), metals and special alloys, plastics (polyurethanes, polypropylenes, polyethylenes, etc.) and rubber and other materials (including so called composite materials), components and electrical and electronic components as well as consumables and auxiliaries (e.g. brake fluid, oil, etc.). The analysis of material inputs was based on the statement of the mass of individual materials that the vehicle consists of.

The tables above also show that between 1990 and 2000 changes in the use of such materials as steel, cast steel, cast iron, aluminum and its alloys and within the use of plastics occurred.

4. Selected example of energy consumption and emission level analysis

In the considered model, the value of specific energy inputs for particular materials and the specific emissions related to them take into account (in compliance with data contained in 11) the whole inputs including the extraction of raw materials and their processing (during the entire processing) to the form of the finished product. This model does not take into account inputs associated with the activities of workers who perform the assembly.

The basis for making the analysis of energy consumption and emission for the construction phase of a motor car is determining its initial material structure, that is the mass summary of individual materials that the particular vehicle consists of after its construction and the individual values of energy inputs (ei), and also the individual emissions (em) for the particular type of material. This way, the volume of cumulative energy inputs (CEI) may be calculated according to the relation below:

$$CEI_{FB} = \sum_{i=1}^{n} m_{i/FB} \cdot ei_i \qquad (8)$$

where: FB – construction phase, $m_{i/FB}$ - mass of the particular material in kg, and ei_i - individual energy inputs for the particular material in MJ/kg.

Whereas, levels of cumulative emissions (CE) for the particular types of emission loads can be calculated according to the following relations:

$$CE_{FB/CO_2} = \sum_{i=1}^{n} m_{i/FB} \cdot em_{i/CO_2} \ , \qquad (9)$$

$$CE_{FB/SO_2} = \sum_{i=1}^{n} m_{i/FB} \cdot em_{i/SO_2} \ , \qquad (10)$$

$$CE_{FB/NO_x} = \sum_{i=1}^{n} m_{i/FB} \cdot em_{i/NO_x} \ , \qquad (11)$$

where: em_{i/CO_2}, em_{i/SO_2}, em_{i/NO_x} are the individual emissions of CO_2, SO_2 and NO_x respectively for the particular material in kg emission/kg material.

Unit values of energy inputs and unit values of harmful substances emissions associated with the production of various types of materials used in the automotive industry were taken from [9].

Figures 3 to 6 present data on the cumulative energy inputs and the cumulative emissions of CO_2, SO_2 and NO_x. Calculations of cumulative energy inputs and cumulative emissions have been done using the EN_VEHICLE program [the authors' own program].

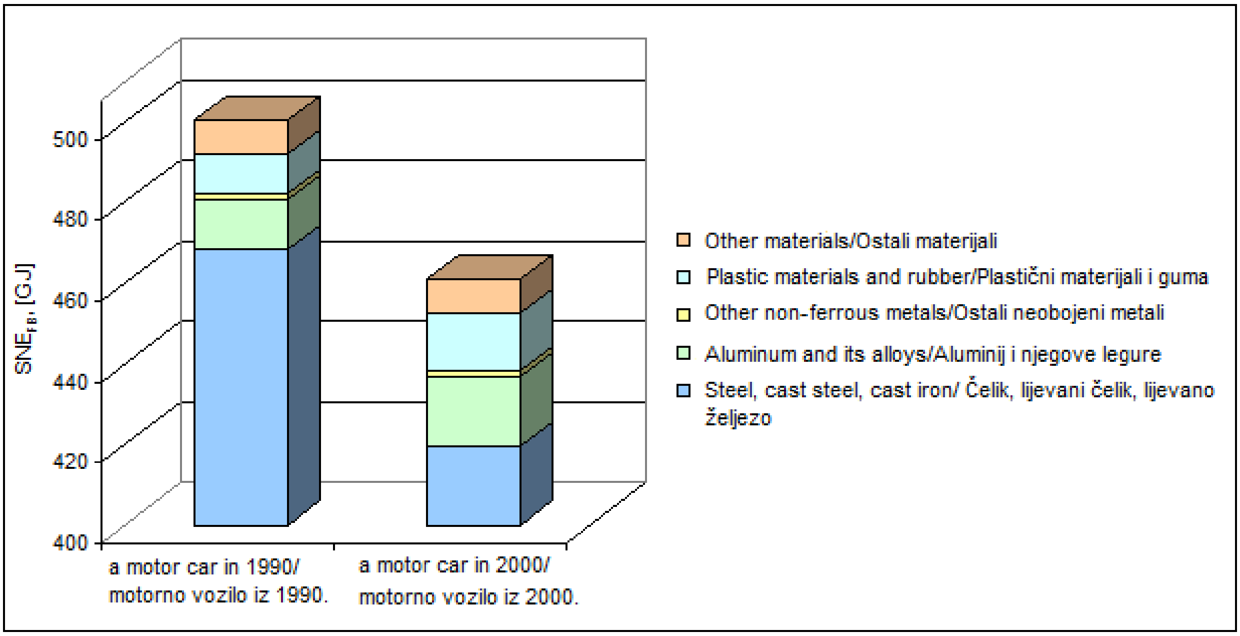

Figure 3. Cumulative energy inputs (CEI) appearing in the construction phase for an example of a motor car in 1990 and 2000

Slika 3. Ukupni ulazni podaci o energiji (CEI) koji se pojavljuju u fazi izrade za primjerak motornog vozila iz 1990. i 2000.

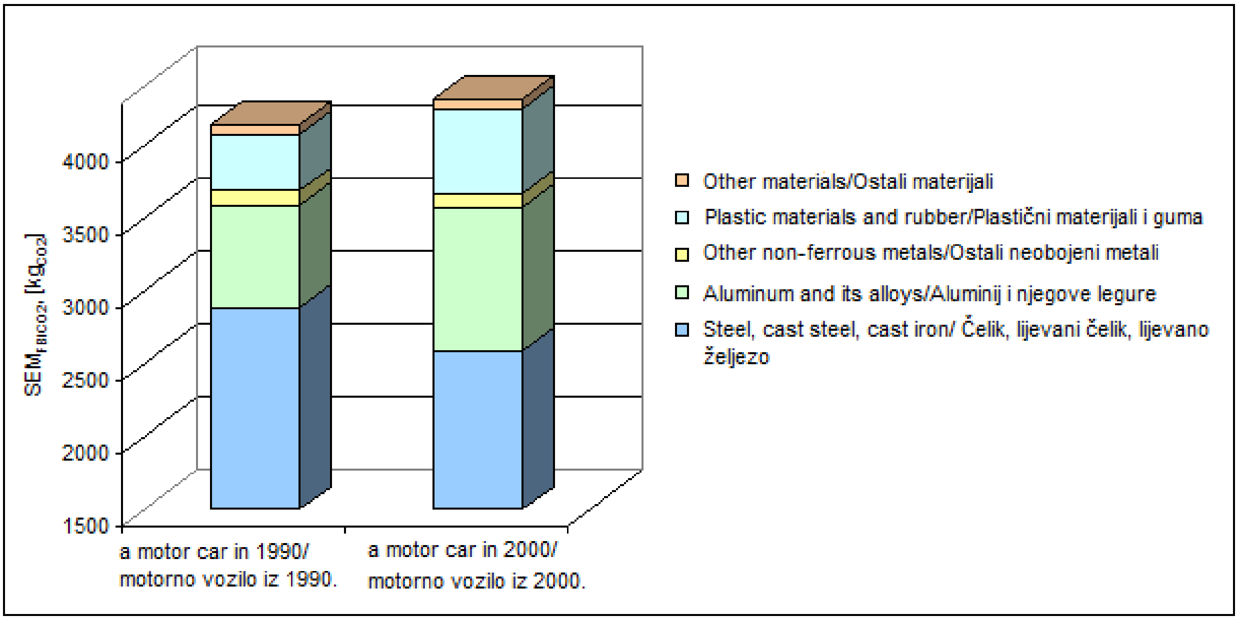

Figure 4. CO2 cumulative emissions appearing in the construction phase for an example of a motor car in 1990 and 2000

Slika 4. Ukupne emisije CO2 koje se pojavljuju u fazi izrade za primjerak motornog vozila iz 1990. i 2000.

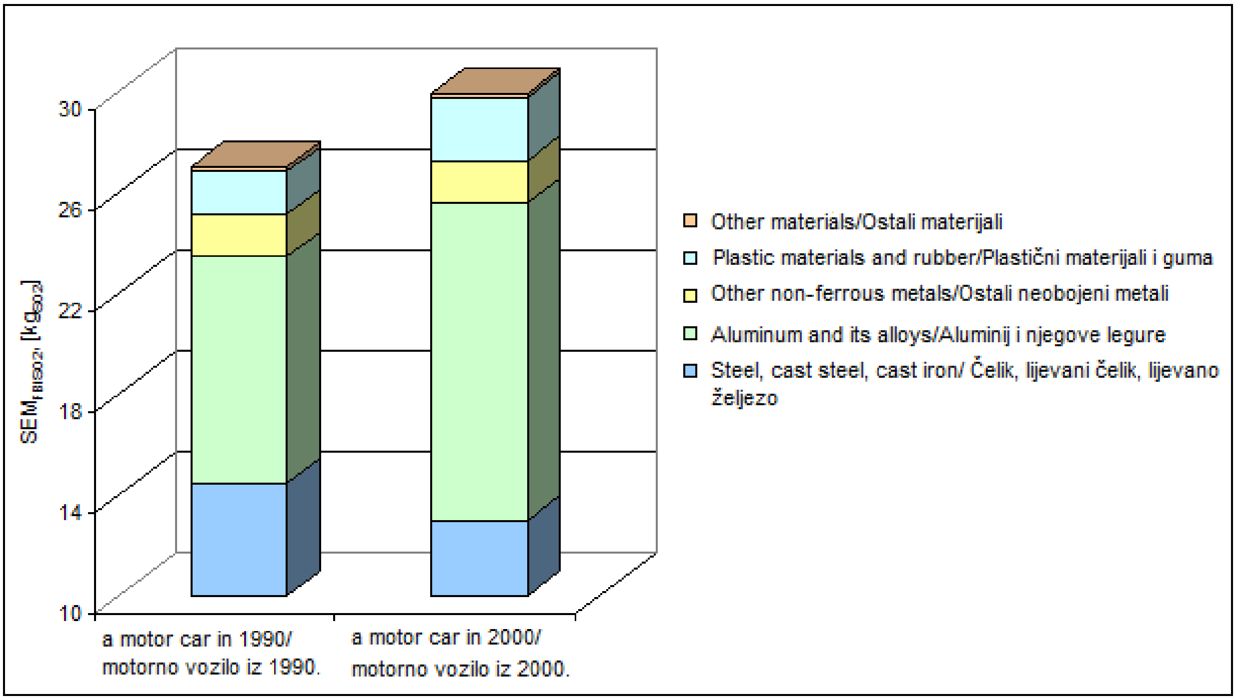

Figure 5. SO_2 cumulative emissions appearing in the construction phase for an example of a motor car in 1990 and 2000

Slika 5. Ukupne emisije SO_2 koje se pojavljuju u fazi izrade za primjerak motornog vozila iz 1990. i 2000.

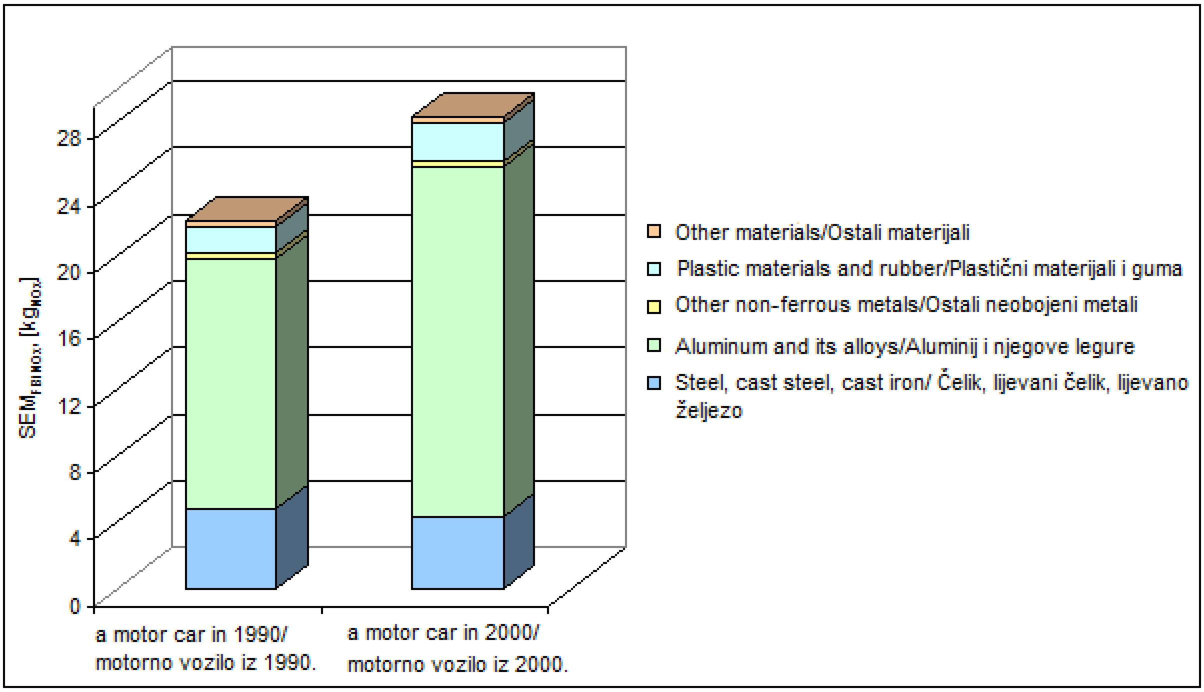

Figure 6. NOx cumulative emissions appearing in the construction phase for an example of a motor car in 1990 and 2000

Slika 6. Ukupne emisije NOx koje se pojavljuju u fazi izrade za primjerak motornog vozila iz 1990. i 2000.

1. CONCLUSIONS

On the basis of these studies and their analysis it was found that:

- cars contains many different materials and their composition and the mass percentage of scrapped cars influences recycling and its costs, and hence the profitability and the consequences for the environment;
- changes in the materials used in the construction of cars are especially visible in the case of the data contained in Table 2, covering the period from 1990 to 2000;
- a significant reduction of materials such as steel, cast steel and cast iron (reduction by more than 10%), for materials such as aluminum and its alloys (an increase of 40%), or plastic and rubber (an increase of 50%) can be seen here;
- we have to manage with the opposite tendency in the case of existing emission levels (see Figures 4, 5 and 6). CO_2 emissions rose by 4.13%, SO2 emissions increased by 10.84% (mainly through the increased participation of plastics), and the level of NO_x emissions rose by 28.46%, which is also associated with more than a 50% increase of plastic percentage within the overall mass balance of the construction phase of cars within a ten-year period between 1990 and 2000.

In conclusion, the changes that have occurred in the structure of consumption of materials in the phase of construction of passenger cars during the past two decades, on the one hand led to a reduction in the related cumulative energy inputs, but on the other hand led to a significant increase in harmful substances emissions into the atmosphere.

Acknowledgements

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