Article citation info:
CHŁOPEK, Z., LASOCKI, J. Life cycle assessment of a car with compression-ignition engine due to the fuel used. *Combustion Engines*. 2013, **154**(3), 183-191. ISSN 0138-0346.

Zdzisław CHŁOPEK
Jakub LASOCKI

PTNSS–2013–SC–006

Life cycle assessment of a car with compression-ignition engine due to the fuel used

Abstract: The paper presents life cycle assessment (LCA) of motor vehicles with compression ignition engines powered with diesel oil, methyl esters of palm, rape, and soybean oils and methyl esters of used vegetable oil. The scope of the analysis included the environmental impact of the processes related to fuel preparation as well as to vehicle manufacturing, operation and disposal when worn out. A balance of the emission of greenhouse gases (GHG) and the consumption of energy obtained from non-renewable sources was compiled. The environmental impact was assessed with the use of the Eco–indicator 99 method. The results obtained have revealed significant differences in environmental loading by specific fuels. In the case of biofuels, a key role is played by the type of the biomass used for the production of fuel, especially by the method of cultivation of the plants to be used as the biomass.

Keywords: *life cycle assessment (LCA), compression–ignition engines, vegetable oil esters, biodiesel*

Ocena cyklu istnienia samochodu z silnikiem o zapłonie samoczynnym ze względu na stosowane paliwa

Streszczenie: W pracy przedstawiono ocenę cyklu istnienia samochodu z silnikiem o zapłonie samoczynnym zasilanym olejem napędowym, estrami metylowymi olejów: palmowego, rzepakowego i sojowego oraz estrami metylowymi zużytego oleju roślinnego. W analizie uwzględniono między innymi oddziaływanie na środowisko procesów związanych z przygotowaniem paliwa, wytwarzaniem samochodu, jego eksploatacją i zagospodarowaniem po zużyciu. Zbilansowano emisję gazów cieplarnianych i zużycie energii ze źródeł nieodnawialnych. Oceny wpływu dokonano metodą Eco–indicator 99. Otrzymane wyniki pozwalają stwierdzić znaczne różnice w obciążeniu środowiska dla poszczególnych paliw. Kluczową rolę w przypadku biopaliw odgrywa rodzaj biomasy wykorzystywanej do wytwarzania paliwa, a w szczególności sposób jej uprawy.

Słowa kluczowe: *ocena cyklu istnienia (LCA), silniki o zapłonie samoczynnym, estry olejów roślinnych, biodiesel*

1. Introduction

Motor vehicles exert an impact on the natural environment for the whole period of their existence, from designing through manufacturing and operation to disposal when worn out [6, 22]. In the case of a motor vehicle with a combustion engine, an important factor that causes this impact is fuel. The environmental impact of fuel is related not only to the pollutant emissions resulting from engine operation but also to various impacts of the fuel preparation process [5, 15]. In consequence, the type of the fuel used may determine to a significant extent the ecological vehicle properties considered in a comprehensive way.

The classic fuels used to power automotive combustion engines are petrol and diesel oil. However, growing interest in unconventional fuels, including biofuels i.e. fuels made by biomass processing, has been observed in the recent decades [1, 4].

Biofuels obtained from materials of agricultural origin have many good points, both ecological and economic: they help to control the global depletion of fossil fuel resources, reduce the dependence of national economies on crude oil supplies, diversify the energy sources available, and stimulate the development of local agriculture [4, 8]; moreover, the use of such fuels results in abatement of the emissions of some toxic substances [1, 4, 8]. The most strongly emphasized ecological aspects of the use of biofuels are their renewability and the possibility of reduction of CO_2 emission, while this gas fosters the intensification of the greenhouse effect in the atmosphere [4, 5, 8]. Obviously, the use of biofuels as such does not directly cause carbon dioxide abatement; nevertheless, the production of raw materials for these renewable fuels entails the absorption of this gas from the atmosphere. In consequence, a significant reduction in the global emission of fossil carbon dioxide becomes thus possible.

Among the biofuels available, those arousing the greatest hopes are fatty acid alkyl esters, commonly known as biodiesel and used to power compression ignition engines. Such a fuel is obtained by transesterification of vegetable oils or animal fats with the use of alcohol, usually methanol or ethanol. Based on the origin of the biomass used in the production process, the fatty acid esters are conventionally divided into two generations [1–5, 15, 24, 17, 20]:

- Esters of the first generation, obtained from raw materials usable in the food industry; the most popular materials used for this purpose are rape oil in Europe, soybean oil in the USA and Brazil, palm oil in Asia, as well as sunflower, corn, coconut, sesame, peanut, and cotton-seed oil;
- Esters of the second generation, obtained from inedible or waste materials, chiefly used fryer oil and marine algae.

In this study, an attempt was made to carry out comprehensive assessment of the environmental impact of a motor vehicle with a compression ignition engine fuelled with diesel oil or methyl esters of various oils of vegetable origin. This was done with the use of the life cycle assessment (LCA) method. For the assessment of the environmental properties of individual fuels to be as objective as possible, the total environmental load caused by a specific fuel during the whole conventional cycle of production, distribution, and use of the fuel was taken into account (according to the "Well-to-Wheel" or "WtW" method [5]). Based on this, the share of fuel preparation processes in the total environmental load caused by the motor vehicle was determined. The analysis results obtained for specific fuels were compared with each other and the fuels were indicated the use of which to power compression ignition engines would be most advisable, from the environmental protection point of view.

2. The life cycle assessment method

The life cycle assessment (LCA) method is an analytical tool for quantitative determining of the potential environmental impact of the processes related to the whole conventional period of existence ("life cycle") of a specific object [6, 16, 18, 19]. General guidelines concerning the LCA, interpretation of results, and models of the documents required have been provided in ISO standards of the 14000 series, with the most important being those numbered as 14040 and 14044. According to them, the investigations carried out with the use of the LCA method should consist of four phases:

- Goal and scope definition;
- Life cycle inventory, LCI;
- Life cycle impact assessment, LCIA;
- Interpretation.

During the first phase, the boundaries of the scope of the analysis are determined. The life cycle of the object under consideration is presented in the form of a system of interrelated unitary processes for which sets of input and output quantities and their units of measure are established. A "functional unit," i.e. a unit of measure which will then be used to quantify the final results of the analysis, is also defined.

The second phase consists in the collection of numerical data on all the input and output quantities. Based on this information, material and energy balances are compiled.

In the third phase of the analysis, potential environmental impacts are assigned to the results of the said balances. The impacts are classified according to the potential effect they might have on the environment. For these purposes, the environmental impacts have been divided by convention into specific impact categories, such as climate change; ozone layer depletion; eutrophication; acidification; smog formation; damage to ecosystem quality; damage to human health; depletion of fossil fuel, mineral raw material, and water resources; or changes to areas with natural ecosystems [6, 16, 18, 19]. The environmental impact of an object may also be assessed in terms of the impact on specific areas of protection (AoP), where such areas are combinations of several impact categories. According to ISO, there are three major types of the areas of protection, i.e. human health, ecosystem quality, and resources [16, 18, 19]. To calculate the environmental impact category indicators from the results of balance of the input and output quantities, a number of impact assessment methods may be used, such as: CML 2002, Eco-indicator 99, EDIP, EPS2000, Impact 2002+, LIME, LUCAS, MEEup, ReCiPe, Swiss Ecological Scarcity, TRACI, or USEtox [6, 16, 18, 19].

The fourth phase of the LCA analysis is a recapitulation of the whole analysis and includes comments to the results obtained and conclusions concerning the three preceding phases.

3. Assumptions and input data

The LCA analysis was carried out to compare the environmental impacts of a motor vehicle with a compression ignition engine fuelled with diesel oil and five types of vegetable oils methyl esters (pure biofuel – B100).

The following symbols have been adopted:

- PO MY – palm oil methyl esters, produced in Malaysia;
- RO UE – rape oil methyl esters, produced in the EU;
- SO BR – soybean oil methyl esters, produced in Brazil;
- SO US – soybean oil methyl esters, produced in the USA;
- UO FR – used vegetable oil methyl esters, produced in France;
- ON – diesel oil.

The scope of the LCA analysis, presented in the form of a diagram in Fig. 1, included:

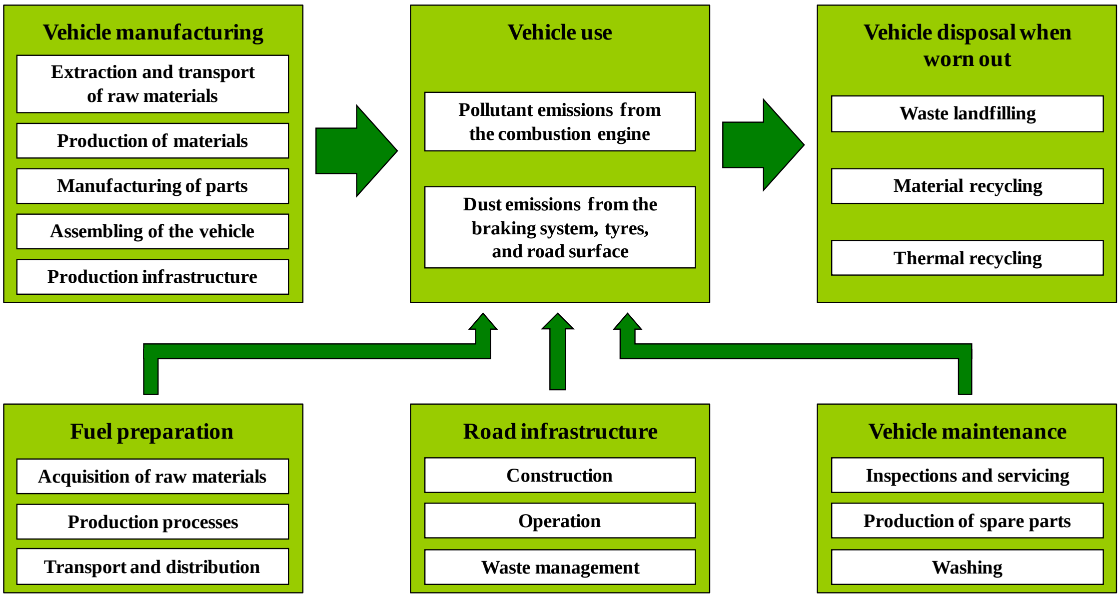

Fig. 1. The vehicle life cycle as considered in this study

- Vehicle manufacturing: extraction of raw materials, production and transport of materials and blanks, making of vehicle parts, assembling of the vehicle, construction and operation of production infrastructure;
- Fuel production: acquisition of raw materials (plant cultivation or crude oil extraction), production processes, and transport of the fuel to Europe and fuel distribution;
- Vehicle use: pollutant emissions from the combustion engine, dust emissions from the braking system, tyres, and road surface;
- Vehicle maintenance: inspections, servicing (with parts replacement), and washing;
- Road infrastructure: construction, operation, and waste management;
- Vehicle end-of-life: waste landfilling, material recycling, waste-to-energy conversion.

The functional unit was assumed as a distance of 1 km travelled by the motor vehicle. The average period of existence of a passenger car with a compression ignition engine in Poland and the number of kilometres annually travelled by such a car were assumed as 15.5 years [12] and 12 000 km [23], respectively.

The quantitative data to be taken for the analysis were obtained from the Swiss Ecoinvent database [15, 22]. In geographic terms, these data were applicable, first of all, to the EU area (vehicle manufacturing, maintenance, and disposal processes) and to the selected countries of origin of the fuels taken into consideration in this study (plant cultivation methods and ester production technologies). The time span of the applicability of these data covered the years from 2000 to 2005.

Numerous investigations were carried out to explore the impact of combustion engine fuelling with esters of vegetable oils on pollutant emissions; results of such works have been extensively discussed in the literature [1–4, 8, 9, 11, 17, 20, 24]. However, detailed numerical data concerning this issue show significant scatter because of different objects tested (engines, complete motor vehicles), test conditions (static and dynamic tests), and fuels used (made from different feedstock, having different composition defined by the volumetric share of esters in the mixture with diesel oil). In a substantial majority of tests, the use of such fuels resulted in reduced carbon monoxide, hydrocarbon, and particulate matter emissions and increased nitrogen oxides emissions in comparison with the figures recorded when the engines were fuelled with diesel oil.

The analysis described herein was carried out on an average passenger car with a compression ignition engine. Therefore, it was based on data applicable to the average passenger car used in the European Union in 2010 and concerning the pollutant emissions from an engine fuelled with diesel oil and the fuel consumption of such an engine [22]; originally, these data were obtained from simulations carried out with the use of the COPERT 4 model [7]. The assumptions concerning the pollutant emissions from an engine fuelled with methyl esters of vegetable oils and the fuel consumption of such an engine were made on the grounds of literature data [2, 3, 17, 20, 24], with taking into account differences in the properties of fuels obtained from different feedstock.

The combustion engine is not the only source of the pollutant emissions that take place when the motor vehicle is used. The wear of friction pairs in the braking system of an average car results in the emission of about 0.5 kg of dust a year. This dust contains a large amount of heavy metals, which are extremely harmful to human health.

The data were inventoried and the life cycle impact was assessed with the use of the SimaPro computer software [13].

The greenhouse gas (GHG) emissions for the whole period of existence of a motor vehicle were calculated as the equivalent carbon dioxide emission in accordance with the IPCC method [21] and the total consumption of energy obtained from non-renewable sources was determined with the use of the Cumulative Energy Demand method [10].

The life cycle impact assessment was carried out with the use of the Eco-indicator 99 (H/A) method [14]. The impact categories and areas of protection have been specified in a table 1. The values of individual impact category indicators have been combined together into a single indicator ("Eco-indicator") in accordance with the assumptions dictated by the hierarchist approach. This indicator is measured in points per the functional unit, which is 1 kilometer in this case, i.e. the unit of measure is pt/km.

Table 1. Impact categories and areas of protection in the Eco-indicator 99 method [14]

Impact category	Area of protection	Indicator unit
Carcinogenic effects	Human health	DALY
Respiratory effects (organics)		
Respiratory effects (inorganics)		
Climate change		
Radiation		
Ozone layer depletion		
Ecotoxicity	Ecosystem quality	$PDF \cdot m^2 \cdot yr$
Acidification / eutrophication		
Land use		
Minerals	Resources	$MJ_{surplus}$
Fossil fuels		

4. Results of the LCA analysis

For the investigation results to be appropriately presented and analysed, the life cycle of a motor vehicle was divided into three general areas (cf. Fig. 1):

1) Motor vehicle and road infrastructure (this covers the processes of vehicle manufacturing, maintenance, and disposal when worn out and the road infrastructure);
2) Fuel preparation (the stage referred to as "Well-to-Tank" or "WtT");
3) Vehicle use (the stage referred to as "Tank-to Wheel" or "TtW").

This division has simplified the interpretation of the analysis results, because an assumption may be made that the environmental load caused by the "vehicle and infrastructure" area does not directly depend on the type of the fuel used.

The greenhouse gas emissions in the life cycle of a motor vehicle per 1 km of the distance travelled by the vehicle have been presented in Figs. 2 and 3. In the former, individual areas of the life cycle have been shown separately, while the latter shows the total emission values.

A predominating source of the GHG emissions in the life cycle of a motor vehicle was found to be the vehicle use (chiefly the fuel combustion), although the investigation results obtained differed from each other depending on the fuel type. This is due to differences in the elemental composition of the fuels under investigation. Obviously, the calorific value of esters, which contain oxygen, is lower than that of diesel oil. The esters obtained from different raw materials also differ from each other in the proportion between the numbers of atoms of hydrogen and carbon and such differences affect the carbon dioxide emission, too.

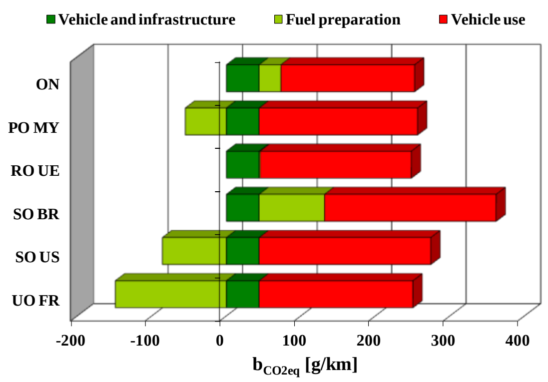

Fig. 2. GHG emissions in the three general areas of the life cycle of a motor vehicle with a compression ignition engine

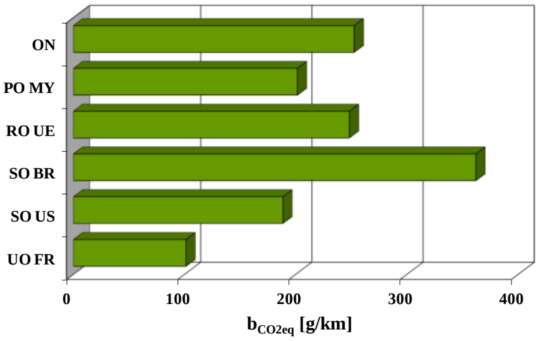

Fig. 3. Total GHG emissions in the life cycle of a motor vehicle with a compression ignition engine

The emission of greenhouse gases from the processes related to road infrastructure and to the manufacturing, maintenance, and and disposal of vehicles was definitely lower than that caused by the vehicle use. The value of this emission is constant by assumption, regardless of the type of the fuel used.

The greatest differences in the GHG emissions occurred in the fuel preparation processes. A characteristic good point of biofuels in respect to the balancing of carbon dioxide emissions is the fact that the mass of carbon dioxide absorbed during the plant growth process may be considered negative (Fig. 2). Unfortunately, it frequently happens that the plant cultivation methods and the plant-to-biofuel processing technology result in high GHG emissions.

The lowest value of the total greenhouse gas emissions in the life cycle of a motor vehicle (Fig. 3) was obtained for the biofuel made from used vegetable oil. The next positions in the feedstock ranking list in this respect are occupied, in succession, by esters of US soybean oil, esters of Malaysian palm oil, esters of rape oil, diesel oil, and, at the end, esters of Brazilian soybean oil. The result obtained for the rape oil is only slightly better than that for the diesel oil; on the other hand, the esters of soybean oil of Brazil were found to be much worse.

According to expectations, the used vegetable oil was found to be the most favourable feedstock in terms of GHG emissions, as the environmental load related to plant cultivation is not taken into account for this material, which is a waste product. The high GHG emissions at the production of soybean oil in Brazil and palm oil in Malaysia arise from the conversion of tropical forests into fields under cultivation. For the rape oil of the European Union, a key role is played by intensive land improvement through the application of nitrogenous fertilizers. Such fertilizers are a source of the emission of dinitrogen monoxide, whose potential in building the greenhouse effect is almost three hundred times as high as that of carbon dioxide. Additionally, high consumption of fossil fuels by agricultural machinery is taken into account. A similar situation takes place in the USA, but there the agriculture is more productive than that in Europe, chiefly due to very advanced specialization and large areas under cultivation.

The consumption of non-renewable energy assignable to the fuels under investigation per 1 km of the distance travelled by the motor vehicle has been presented in Fig. 4.

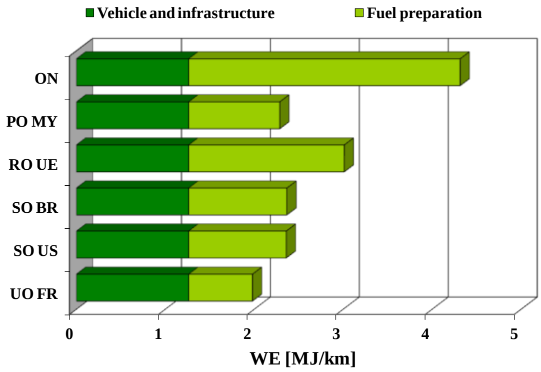

Fig. 4. Consumption of non-renewable energy in the life cycle of a motor vehicle with a compression ignition engine

The consumption of non-renewable energy in the life cycle of a motor vehicle powered with biofuels is much lower than that observed in the case of diesel oil being used as a fuel. This is because of high energy intensity of crude oil processing. The best result was obtained for esters of used vegetable oil. The second best position is occupied by esters of palm oil and soybean oil, whether the latter are produced in the USA or Brazil. Esters of rape oil have the worst properties in this respect, chiefly because of the high consumption of fossil fuels by the agricultural machinery as mentioned above and the significant degree of farm fragmentation in Europe.

The nitrogen oxides and particulate matter emissions for the fuels under investigation per 1 km of the distance travelled by the motor vehicle have been shown in Figs. 5 and 6, respectively.

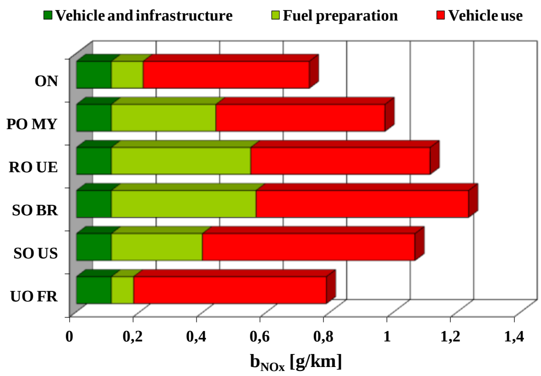

Fig. 5. Nitrogen oxides emissions in the life cycle of a motor vehicle with a compression ignition engine

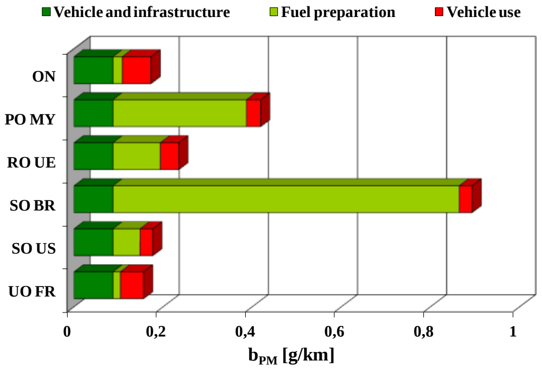

Fig. 6. Particulate matter emissions in the life cycle of a motor vehicle with a compression ignition engine

For a motor vehicle with a compression ignition engine, a key role in the emissions of nitrogen oxides, which are very harmful to human health, is played by the vehicle use. Esters of vegetable oils are inferior in this respect to diesel oil. Moreover, they are also susceptible to the fuel preparation process. Only for the esters of used vegetable oil, the emission of nitrogen oxides is close to that for diesel oil.

The investigation results regarding the particulate matter emissions are irregular to some extent. Extremely high values of this indicator were obtained for the fuels from Brazil and Malaysia, which is a consequence of converting rainforests into agricultural land. Two of the biofuels under investigation, i.e. esters of used vegetable oil and US made esters of soybean oil, show particulate matter emission properties being better than those of diesel oil.

Results of the motor vehicle life cycle impact assessment carried out in accordance with the Eco-indicator 99 method have been presented in Figs. 7 and 8. The former one shows the environmental load in terms of the general areas of the life cycle of the motor vehicle as adopted for this study; the environmental load presented in the latter graph has been shown in terms of the three standardized areas of protection, i.e. human health, ecosystem quality, and resources, according to ISO.

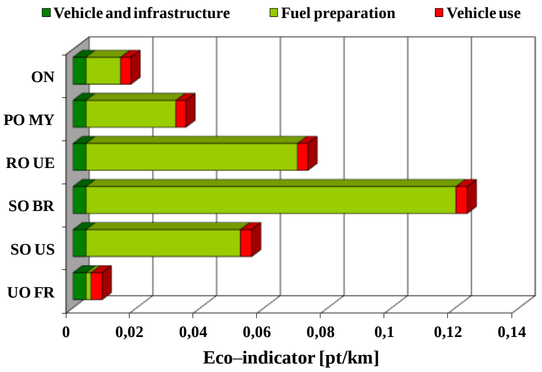

Fig. 7. Environmental impact of a motor vehicle with a compression ignition engine, shown in terms of the general areas of the vehicle life cycle

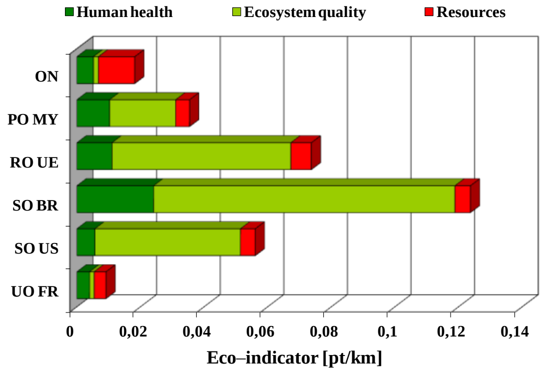

Fig. 8. Environmental impact of a motor vehicle with a compression ignition engine, shown in terms of the areas of protection

Based on results of the comprehensive assessment of the environmental impact of the motor vehicle, obtained with the use of the Eco-indicator 99 method, a statement may be made that the fuelling of compression ignition engines with methyl esters of vegetable oils of the first generation is not an advisable solution. This is chiefly a consequence of high environmental load caused by the current biomass acquisition and processing methods. In comparison with them, the diesel oil production technology, having been improved for many years, has much better ecological properties. Only the esters of used vegetable oil, i.e. a biofuel of the second generation made from waste materials, whose total environmental impact is estimated at about a half of that of diesel oil, make an exception to this finding.

An analysis of the results presented in Fig. 8 reveals differences in the nature of the environmental impact of the fuels under investigation. For the diesel oil, the highest environmental load is obviously related to the depletion of resources. The human health has been placed on the second position of this ranking list and the ecosystem quality has been found to be an issue of minor importance. For the biofuels of the first generation, the ecosystem quality has been found to be the most important area of protection (where the hazard is chiefly related to the plant cultivation); the second one is the human health (where the nitrogen oxides emissions are of significant importance); the depletion of resources has only been placed third. For the biofuel of the second generation, the most important areas of protection are the human health and the resources, according to the analysis results, with no significant hazard being posed by this fuel to the ecosystem quality.

The results of the life cycle impact assessment should be interpreted with bearing in mind the significant stress being put in the Eco-indicator 99 (H/A) method on the "land use" impact category, counted within the "ecosystem quality" area of protection. Hence, the results obtained for the fuels under investigation have been determined to a considerable extent by the indicator value for this impact category (see Fig. 9).

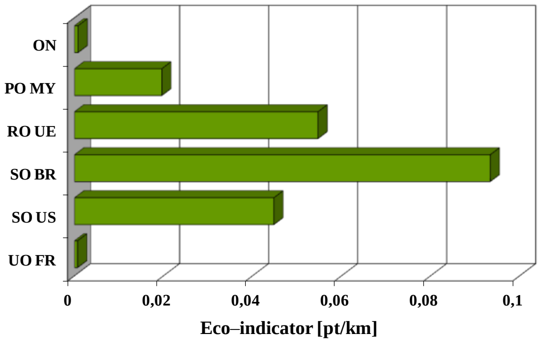

Fig. 9. Environmental impact of a motor vehicle with a compression ignition engine in the "land use" impact category according to the Eco-indicator 99 method

5. Conclusions

Based on the investigations carried out, the following conclusions can be formulated:

1) An important role in the life cycle assessment of a motor vehicle is played by the type of the fuel used, especially the technology and materials employed for the fuel production. Therefore, the powering of combustion engines with unconventional fuels, e.g. biofuels, may be an effective method to reduce the harmful environmental impact of motor vehicles.
2) The biofuels of the first generation used for powering compression ignition engines, with esters of vegetable oils such as rape oil, soybean oil, and palm oil being now the most popular among them, are characterized by high environmental load caused by the plant cultivation and processing into fuel. A comprehensive assessment of the ecological properties of a motor vehicle provides grounds for a statement that the use of biofuels of the first generation is inferior to the use of diesel oil as a fuel.
3) In the case of biofuels of the second generation, obtained from waste materials, e.g. used vegetable oil, the environmental impact of the biomass acquisition processes is not taken into account; therefore, the use of such biofuels to power compression ignition engines is beneficial for the ecological properties of motor vehicles.
4) The investigations carried out with the use of the LCA method should be considered very prudently. In particular, the results of such analyses should be interpreted with taking into consideration the assumptions made. The results obtained with the use of different impact assessment methods, which were based on different assumptions, cannot be compared with each other, either.

Nomenclature/*Skróty i oznaczenia*

LCA Life Cycle Assessment/*ocena cyklu istnienia*
LCI Life Cycle Inventory/*analiza zbioru*
LCIA Life Cycle Impact Assessment/*ocena wpływu cyklu istnienia*
ON diesel oil/*olej napędowy*
PO MY palm oil methyl ester from Malaysia/*estry metylowe oleju palmowego z Malezji*
RO UE rape oil methyl ester from European Union /*estry metylowe oleju rzepakowego z Unii Europejskiej*
SO BR soybean oil methyl ester from Brasil/*estry metylowe oleju sojowego z Brazylii*
SO US soybean oil methyl ester from United States of America/*estry metylowe oleju sojowego ze Stanów Zjednoczonych Ameryki*
TtW Tank–to–Wheel/*od zbiornika (paliwa) do koła (pojazdu)*
UO FR used oil methyl ester from France/*estry metylowe zużytego oleju roślinnego z Francji*
WtT Well–to–Tank/*od źródła (pozyskiwania nośnika energii) do zbiornika (paliwa)*
WtW Well–to–Wheel/*od źródła (pozyskiwania nośnika energii) do koła (pojazdu)*
ZS compression ignition engine/*silnik o zapłonie samoczynnym*

Bibliography/*Literatura*

[1] Agarwal A. K.: Biofuels (alcohols and biodiesel) applications as fuels in internal combustion engines. Progress in Energy and Combustion Science vol. 32, pp. 233–271, 2007.
[2] Bakeas E., Karavalakis G., Stournas S.: Biodiesel emissions profile in modern diesel vehicles. Part 1: Effect of biodiesel origin on the criteria emissions. Science of the Total Environment vol. 409, No. 9, pp.1670–1676, 2011.
[3] Cecrle E., Depcik C., Duncan A., Guo J., Mangus M., Peltier E., Stagg–Williams S., Zhong Y.: Investigation of the Effects of Biodiesel Feedstock on the Performance and Emissions of a Single–Cylinder Diesel Engine. Energy and Fuels vol. 26, pp. 2331–2341, 2012.

[4] Chłopek Z.: Zastosowanie biopaliw w transporcie. Konferencja Naukowa „Transport 2008”, Lublin, 7 marca 2008 r.
[5] Chłopek Z., Lasocki J.: Comprehensive evaluation of the environmental hazard caused by the operation of automotive vehicles. The Archives of Automotive Engineering vol. 54, No. 4, pp. 19–36, 2011.
[6] Chłopek Z., Lasocki J., Kieracińska A.: The use of the Life Cycle Assessment of motor vehicles in the evaluation of the impact of motorization on the environment. The Archives of Automotive Engineering vol. 59, No. 1, pp. 15–31, 2013.
[7] COPERT 4 – Methodology and emission factors. European Environment Agency. European Topic Center on Air Emission, 2005.
[8] Demirbas A.: Political, economic and environmental impacts of biofuels: A review. Applied Energy vol. 86, pp. 108–117, 2009.
[9] Fontaras G., Kousoulidou M., Karavalakis G., Bakeas E., Samaras Z.: Impact of straight vegetable oil–diesel blends application on vehicle regulated and non–regulated over legislated and real world driving cycles. Biomass and Bioenergy vol. 35, No. 7, pp. 3188–3198, 2011.
[10] Frischknecht R., Althaus H. J., Doka G., Hischier R., Hellweg S., Jungbluth N., Kellenberger D., Nemecek T., Pennington D. W., Spielmann M.: Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Invetories, Dübendorf 2003.
[11] Giakoumis E. G.: A statistical investigation of biodiesel effects on regulated exhaust emissions during transient cycles. Applied Energy vol. 98, pp. 273–291, 2012.
[12] GUS: Transport – wyniki działalności w 2010 r. Zakład Wydawnictw Statystycznych, Warszawa 2011
[13] Goedkoop M., de Schryver A., Oele M., Durksz S., de Roest D.: Introduction to LCA with SimaPro 7. PRé Consultants, Amersfoort 2010.
[14] Goedkoop M., Spriensma R.: The Eco–indicator 99: A damage oriented method for Life Cycle Impact Assessment. Methodology Report. PRé Consultants, Amersfoort, 2001.
[15] Jungbluth N., Chudacoff M., Dauriat A., Dinkel F., Doka G., Faist Emmenegger M., Gnansounou E., Kljun N., Schleiss K., Spielmann M., Stettler C., Sutter J.: Life Cycle Inventories of Bioenergy. Ecoinvent report No. 17. Swiss Centre for Life Cycle Inventories. Dübendorf 2007.
[16] Kowalski Z., Kulczycka J., Góralczyk M.: Ekologiczna ocena cyklu życia procesów wytwórczych (LCA). Wydawnictwo Naukowe PWN, Warszawa 2007.
[17] Kumar N., Varun, Chauhan S. R.: Performance and emission characteristics of biodiesel from different origins: A review. Renewable and Sustainable Energy Reviews vol. 21, pp. 633–658, 2013.
[18] Pennington D. W., Potting J., Finnveden G., Lindeijer E., Jolliet O., Rydberg T., Rebitzer G.: Life cycle assessment Part 2: Current impact assessment practice. Environment International vol. 30, No. 5, pp. 721–739, 2004.
[19] Pieragostini C., Mussati M. C., Aguirre P.: On process optimization considering LCA methodology. Journal of Environmental Management vol. 96, No. 1, pp. 43–54, 2012.
[20] Rakopoulos C. D., Antonopoulos K. A., Rako–poulos D. C., Hountalas D. T., Giakoumis E. G.: Comparative performance and emissions study of a direct injection Diesel engine using blends of Diesel fuel with vegetable oils or bio–diesels of various origins. Energy Conversion and Management vol. 47, No. 18–19, pp. 3272–3287, 2006.
[21] Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K. B., Tignor M., Miller H. L. (red.): Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge 2007.
[22] Spielmann M., Dones R. Bauer C.: Life Cycle Inventories of Transport Services. Final report ecoinvent v2.0 No. 14. Swiss Centre for Life Cycle Inventories, Dübendorf 2007.
[23] Waśkiewicz J., Radzimirski S., Chłopek Z., Taubert S.: Opracowanie metodologii prognozowania zmian aktywności sektora transportu drogowego (w kontekście ustawy o systemie zarządzania emisjami gazów cieplarnianych i innych substancji). Praca ITS nr 7101/ITS, Warszawa 2011.
[24] Wu F., Wang J., Chen W., Shuai S.: A study on emission performance of a diesel engine fueled with five typical methyl ester biodiesels. Atmospheric Environment vol. 43, No. 7, pp. 1481–1485, 2009.

Prof. Zdzisław Chłopek, DSc., DEng. – Professor at the Faculty of Automotive and Construction Machinery Engineering at Warsaw University of Technology.

Prof. dr hab. inż. Zdzisław Chłopek – Profesor na Wydziale Samochodów i Maszyn Roboczych Politechniki Warszawskiej.

Mr Jakub Lasocki, MSc., Eng. – Engineer in the Automotive Industry Institute in Warsaw, PhD student at the Faculty of Automotive and Construction Machinery Engineering at Warsaw University of Technology.

Mgr inż. Jakub Lasocki – Inżynier w Przemysłowym Instytucie Motoryzacji w Warszawie, doktorant na Wydziale Samochodów i Maszyn Roboczych Politechniki Warszawskiej.

The scientific work of Jakub Lasocki has been supported by the European Union in the framework of European Social Fund through the Warsaw University of Technology Development Programme.