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Chains of Causality Associated with the Environmental Impact of Road Transport System

Mihaela Condurat

Technical University „Gh. Asachi" from Iasi, Romania
Faculty of Civil Engineering and Building Services

*Corresponding author: **conduratmihaela@yahoo.com**

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Given the growing interest in the promotion of sustainable transport worldwide, the measurement and assessment of sustainability associated with systems and transport policies had become an increasingly important area, its measurement being performed through the environmental indicators. The paper presents the main environmental indicators assign to the road transport system and the corresponding chains of causality. Also, the energy performance and the Global Warming Potential, expressed in quantities of CO_2 equivalent, related to the construction and maintenance of flexible road pavements, determined based on a Life Cycle Assessment (LCA) analysis embedded in the asPECT software, developed by TRL Laboratories, are given within this study. This paper aims to emphasize the necessity to take appropriate measures for road pavements maintenance and intervention, intended to prolong their life in order to minimize the overall ecological impact associated with the reconstruction of road pavement, which involves the release into the atmosphere of polluting emissions, usage of enormous granular materials quantities and energy consumption and thus, the exponential increase in the greenhouse effect.

KEYWORDS: chain of causality, CO2e emissions, environmental impact, environmental indicator, transport system.

Introduction

As a consequence of the alarming increase in pollution levels during the last years worldwide, the need to promote sustainable transport models had appeared. These patterns are being used for measurement and assessment of current and future trends regarding sustainability in the global concept of sustainable development. The quantification of transport systems sustainability can be performed based on environmental indicators. Such indicators can be used for identify, monitor and assess environmental issues in decision making processes, as well as in comparative analysis of transport policies, plans, projects or transport technologies.

An environmental indicator is defined through a parameter describing environmental state and its associated impact on human beings, ecosystems and materials, the environmental pressures, driving forces and the system responses, being determined by a complex process of selection (EEA, 2009). Environmental indicators differ according with the chain of causality taken into account. Thus, the chain of causality represents a homogeneous process between the transporta-

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tion system and the environmental impact final result, produced in one step or more. The chain of causality notion is being used in order to interpret the precept of "environmental mechanism", which is defined in the Life Cycle Impact Assessment methodology through biological processes, physical and chemical specific for a particular category of impact (ISO, 2006). In order to apply this chains of causality for practical assessment of transport impacts, it is necessary to perform a thorough inquiry of them and also an identification on how intermediate impacts are dependent to individual and combined variables or decisional parameters of transport systems (Jourmard and Gudmundsson, 2010).

Chains of causality associated with the environmental impact of the transport system

According to recent studies (Jourmard and Gudmundsson, 2010), the transport system has a number of 49 homogeneous chains of causality, which lead to the rise of various categories of environmental impact. The chains of causality and their hierarchy are shown in Table 1.

Table 1

Chains of causality associated with transport activities

Production of noise and vibrations
Accidents
Air pollution
Soil and water pollution
Impacts on land
Non-renewable resource use and waste handling
Greenhouse effect
Other impacts

Production of noise and vibrations

The increase in noise levels triggers serious social and behavioral effects, such as discomfort and sleep disorders. Effects on human health consist in hearing impairment, speech intelligibility, aggravation of physiological and psychological disorders, such as hypertension associated with exposure to high levels of noise or mental illness and reducing cognitive performance (Jourmard and Gudmundsson, 2010).

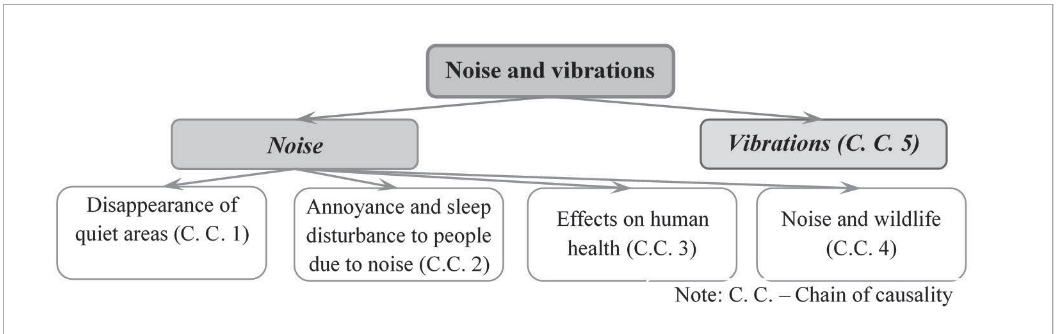

Fig. 1

Chain of causality associated with noise and vibrations from road traffic (Jourmard and Gudmundsson, 2010)

The environmental indicators specific to noise chain of causality associated with the movement of vehicles (see Fig. 1) can be divided into three main classes, namely:

- Noise level indicators: are being used to describe the traffic noises according with their physical and energetic characteristics;

- Noise exposure indicators: are being used to describe the noise effects on exposed individuals in terms of magnitude and territorial expansion;
- Noise annoyance indicators: they characterize the discomfort experienced by those exposed to noise.

Accidents

According with recent studies (World Health Organization, 2010), road accidents produce about 1.24 million fatalities per year, meaning 2.2% of total mortality in 2010. Based on this assessment, a predominant increase of 2.4 million in fatalities by 2030 had been estimated, unless appropriate action is being taken. Fig. 2 shows the corresponding chains of causality associated with road accidents.

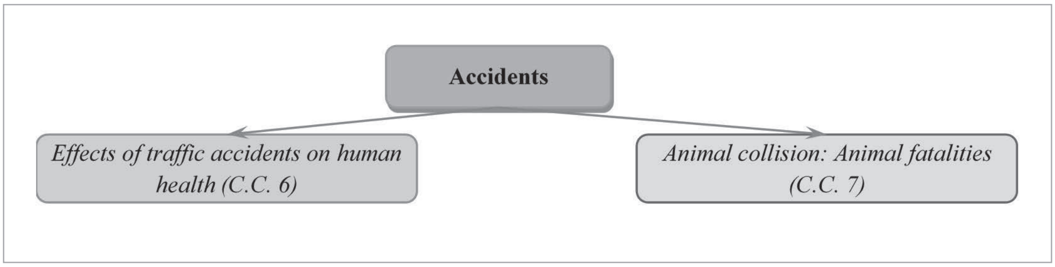

Fig. 2
Chain of causality associated with accidents production (Jourmard and Gudmundsson, 2010)

Air pollution

According Fig. 3, the chains of causality associated with air pollution relates to odors produced as a consequence of SO_2 and volatile organic compounds emissions, particle contamination, decreased visibility, pollutants toxicity and photochemical pollution.

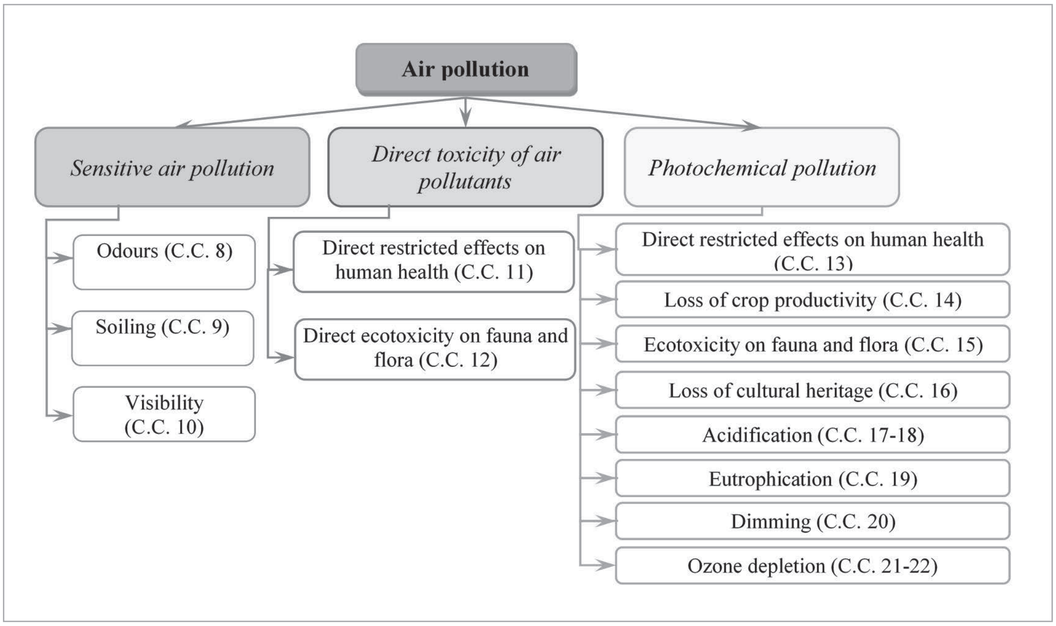

Fig. 3
Chain of causality associated with air pollution (Jourmard and Gudmundsson, 2010)

Soil and water pollution

The chain of causality associated with soil and water pollution is broken down into three main categories, namely soil, surface water and groundwater, marine pollution and hydraulic changes (see Fig. 4).

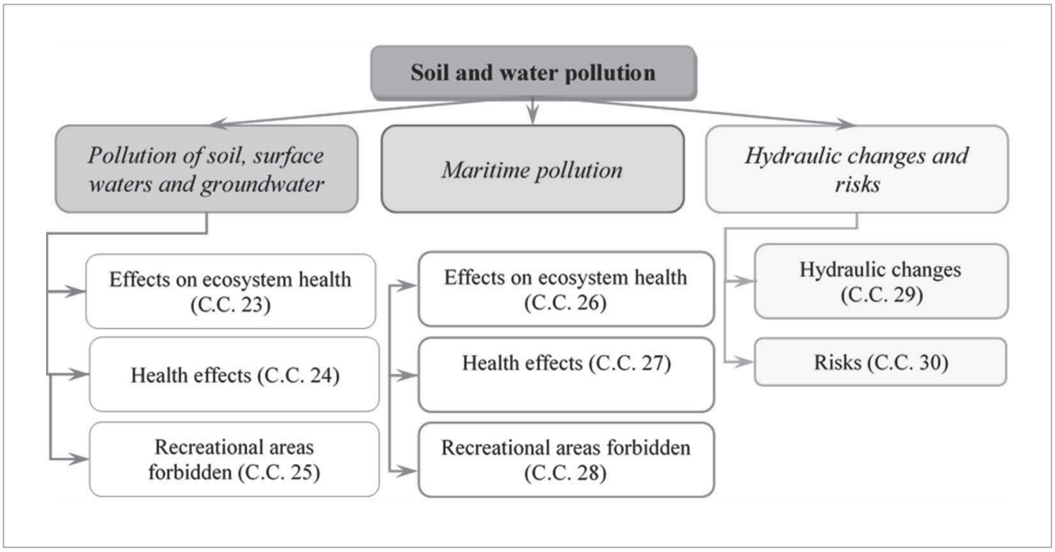

Fig. 4

Chain of causality associated with soil and water pollution (Jourmard and Gudmundsson, 2010)

Impacts on land

According Fig. 5, the impact of the transport system on the land refers to land take, habitat fragmentation, soil erosion and degradation and alteration of landscapes.

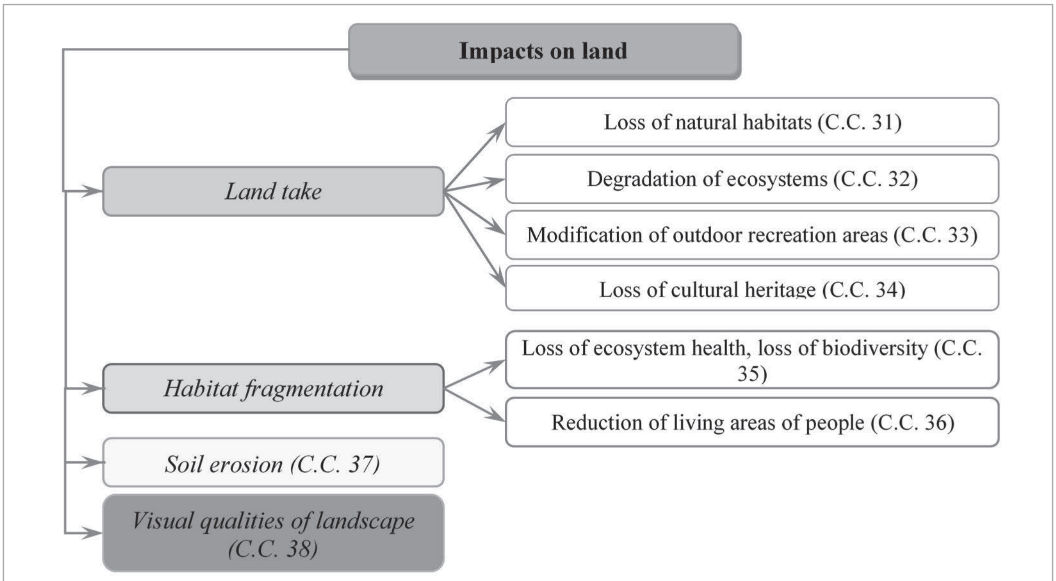

Fig. 5

Chain of causality associated with impact on land (Jourmard and Gudmundsson, 2010)

In the case of habitat fragmentation, the main indicators describing this phenomenon are composition, shape and connectivity indicators of the inhabited area (Rutledge, 2003).

The indicators describing the basic characteristics of habitat fragmentation composition, are represented by the number and range of inhabited area. In the assessment of infrastructure projects, these indicators are being used to determine the minimum area of individual habitats.

The shape indicators quantify the complexity of corresponding habitat areas. The areas could be homogeneous (with a circular shape) or a more complicated geometrical shape (Didier and Thompson, 2010).

The connectivity indicators measure the connectivity degree of inhabited area or isolation between areas. Connectivity is a key element of the habitat structure and is defined by the extent to which some obstacles obstruct the movement of the species between different areas (Tortorec, 2013).

Non-renewable resource and waste handling

Non-renewable resources are of particular interest in the transport, being used as well as energy sources (fossil fuels) and as construction materials. Since the rate of their regeneration is very limited, it is essential to develop fuels and alternative energy sources and to recycle existing structures in order to limit existing current dependence on non-renewable materials (see Fig. 6).

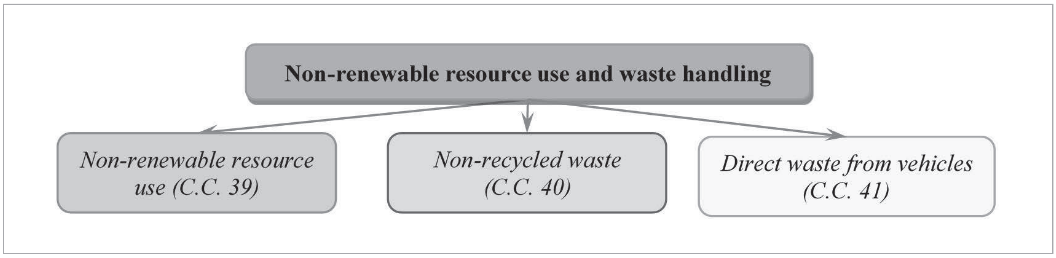

Fig. 6

Chain of causality associated with non-renewable resource use and waste handling (Jourmard and Gudmundsson, 2010)

Greenhouse effect

The most significant indicators describing the greenhouse effect are: Global Warming Potential (GWP), Global Temperature Change Potential (GTP) and health indicator of greenhouse effect impact. GWP expresses the contribution of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6) to global warming.

Further, the paper will present the influence of construction and maintenance processes and technologies specific with asphalt road pavements associated with the greenhouse effect chain of causality through a Life Cycle Assessment analysis conducted according to the methodology incorporated into the asPECT software, version 3.1.

Methods

Given the high levels of pollution nowadays and the fact that, according to European Commission, transport is responsible for 32% of Europe's energy consumption and 28% of total CO_2 emissions, the development of sustainable road construction technologies and processes is more and more important. Furthermore, besides the initial construction of a road pavement, the maintenance and rehabilitation strategies that will be applied represent a major factor in reducing the carbon footprint and, in the same time, in increasing the service life of the road. Also, a significant role in decreasing polluting emissions is played by the moment of intervention. If an intervention strategy is applied at an optimum point in the road lifetime, the costs and the raw materials and energy consumption will be minimum and the service life of the road will be extended. Otherwise, if the road is not rehabilitated when needed, the distresses progress exponentially, leading to the inability to use the road on full safety and comfort conditions. Additionally, the rehabilitation investments, seen both in a financial perspective, as well as in terms of material consumption and labor required, will be directly correlated with the exacerbation of greenhouse effect.

The paper presents the results of recent research undertaken for the quantitative assessment of CO_2 equivalent emissions and energy consumption related to the construction and maintenance of a flexible road pavement using a **Life Cycle Assessment Analysis** incorporated into the asPECT software.

asPECT software methodology

asPECT software, Version 3.1, developed by Transport Research Laboratory - TRL UK, provides a methodology for calculating greenhouse gas emissions during the pavement life cycle produced by using bituminous materials on roads. The asPECT software enables the assessment of CO_2e emissions based on information collected concerning materials, transport and mixture plant characteristics (TRL, 2014). The software database contains the necessary formulas and emission factors for calculating CO_2e emissions associated with the production, laying and maintenance of bituminous layers by taking into consideration all the stages of materials and energy production and all the processes from raw material extraction, production, transport and use phase of the asphaltic mixture to the end of their life (Cradle to Gate), shown in **Fig. 7**.

The process for calculating the CO_2e emissions associated to bituminous road pavement consists of three main stages, namely:

A. The introduction of raw materials used in the asphalt mixture (total annual energy consumption for the acquisition, broken down by type of fuel and operation);

B. Data introduction regarding the asphalt mixes plant characteristics (plant type, annual production, energy consumption and asphalt mix composition);

C. Data introduction regarding installation of bituminous mix and visualization of the results.

The study based on environmental grounds of road infrastructure was performed through a **Life Cycle Assessment Analysis**. The Case Study deals specifically with road pavement intervention strategies carried out using various rehabilitation alternatives. The Life Cycle Assessment Analysis was conducted on the entire built section of 1000 ml long and 7.0 m wide using a **CRADLE TO GRAVE** option, presented in **Fig. 7**. The Global Warming Potential, expressed in terms of CO_2e emissions has been assessed using the asPECT software, version 3.1.

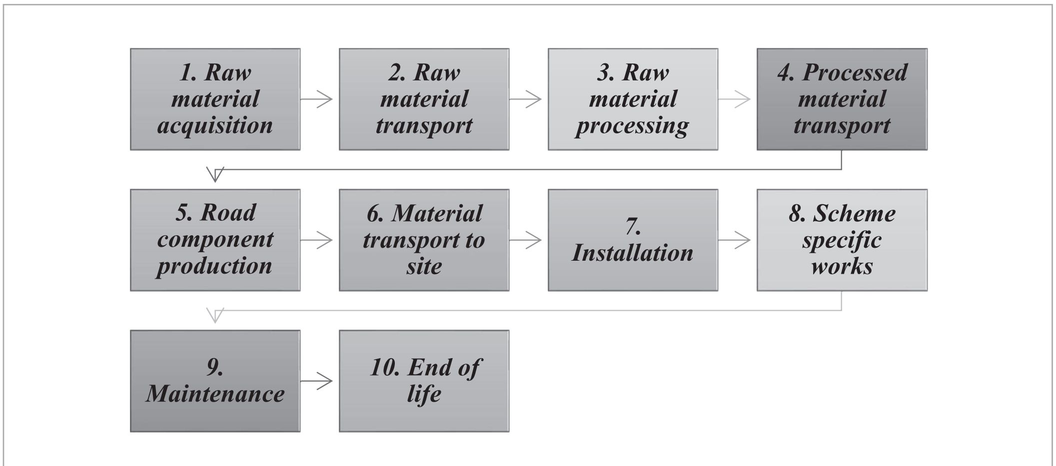

Fig. 7

The life cycle stages of asphalt mixtures Cradle to Grave (TRL, 2014)

Methods

The simple surface treatment

This strategy is performed in a single layer and consists in spreading a uniform continuous coating of bituminous binder, followed by spreading a layer of natural aggregates. Due to the application of this intervention strategy are emitted into the atmosphere **144.75 kg CO_2e/t,** the total being equal with **42760.33 kg CO_2e**.

Slurry seal

Cold thin bituminous layers (slurry seal) are made of asphalt-based emulsions and polymer modified bitumen and can be applied in one coat or two, being used to repair a road pavement by completely sealing the surface. The results of the quantitative assessment of greenhouse gas emissions associated to the execution of slurry seal are shown in Table 2.

Table 2

Emissions associated with the execution of slurry seal

No.	Life Cycle Stage	kg CO_2e/t	Total kg CO_2e
1-3	Material extraction and processing	43.89	6144.42
4	Transport to plant	40.32	5645.08
5	Asphalt production	49.96	6994.68
6	Transport to site	9.10	1274.42
7	Laying and compacting	4.70	658.00
8	Project works	0.00	0.00
9	Maintenance	0.00	0.00
10	Reconstruction	16.70	2338.00
Stages 1-7 (140 tons slurry seal)		**164.8**	**23054.59**

Thin overlays

Thin overlay ¾ inch is a means of maintenance and rehabilitation of existing road pavement by applying a thin layer of asphalt mixture. This process is used to repair damages like weathering and raveling, bleeding, minor cracks, etc. and is used to enhance the road surface characteristics and not the structural ones. Table 3 presents the quantities of CO_2e associated with thin layers reinforcement.

Table 3

CO_2e emissions associated with thin layers reinforcement (thin overlay ¾ inch)

No.	Life Cycle Stage	kg CO2e/t	Total kg CO2e
1-3	Material extraction and processing	48.8	14809.89
4	Transport to plant	34.81	10722.15
5	Asphalt production	47.83	14731.27
6	Transport to site	30.17	9292.62
7	Laying and compacting	4.70	1447.60
8	Project works	0.00	0.00
9	Maintenance	0.00	0.00
10	Reconstruction	16.70	5143.60
Stages 1-7 (308 t mixture)		**182.30**	**56147.13**

Heat planner and 1” AC

Heat planner and 1” AC” consist in heating the road pavement surface, milling to a certain depth of the layer and mixing the resulting material with bituminous emulsion, after which the obtained mixture is spread and compacted accordingly. Greenhouse gas emissions related to this process are presented in Table 4.

Table 4

CO_2e emissions associated with heat planner and 1" AC

No.	Life Cycle Stage	kg CO_2e/t	Total kg CO_2e
1-3	Material extraction and processing	54.28	21167.33
4	Transport to plant	31.50	12284.36
5	Asphalt production	1.00	389.75
6	Transport to site	30.17	11766.63
7	Laying and compacting	4.70	1833.00
8	Project works	0.00	0.00
9	Maintenance	0.00	0.00
10	Reconstruction	16.70	6513.00
Stages 1-7 (390 t mixture)		**121.64**	**53954.07**

Reconstruction of a new road flexible pavement

Finally, taking into consideration the same assumptions defined above, the effect on the environment associated with road reconstruction has been measured and the final results of the impact assessment are given in Table 5. Fig. 8 shows the life cycle stages and the supply chain associated with the reconstruction of a new road pavement.

In this respect, it has been selected a bituminous road pavement consisting in the following layers:

- Wearing course (BA16, 4 cm – 644 tone);
- Binder course (BAD25, 6 cm – 945 tone);
- Base course (AB2, 15 cm – 2258 tone);
- Foundation layer (ballast, 20 cm);
- Subgrade (20 cm).

Note:

BA 16 – asphalt concrete with the maximum size of the aggregate of 16 mm

BAD 25 - asphalt concrete with the maximum size of the aggregate of 25 mm

AB – asphalt base

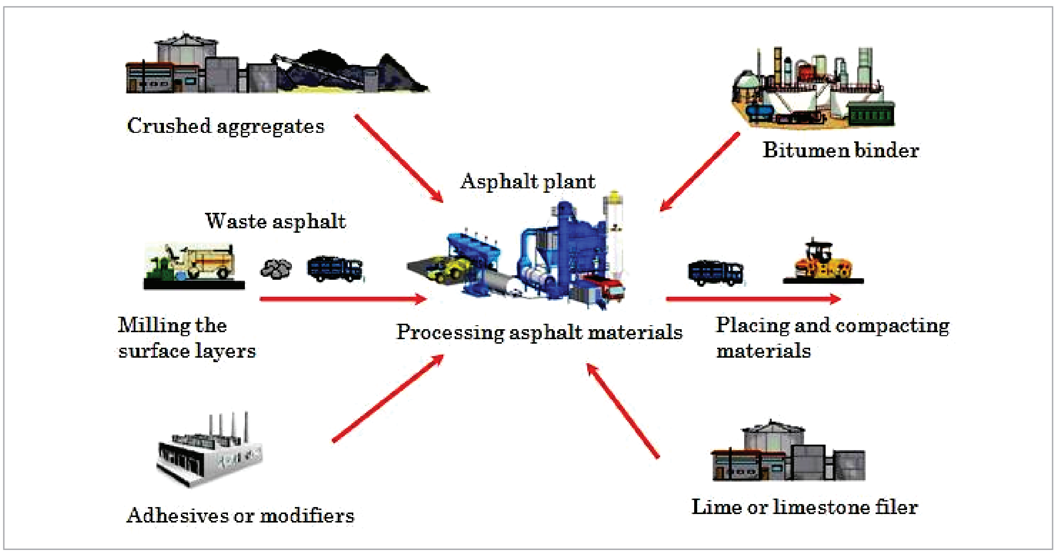

Fig. 8

Consideration of the whole processing chain from Cradle (resource extraction) to fabrication and layering the mix on the road site (Andrei, et al., 2016)

Also, besides the construction of asphalt layers, it has been considered and the execution of surface dressing and retexturing in the frame of in-situ maintenance with an extension of service life of 4 and 6 years.

Table 5

CO_2e emissions associated with the construction of a new road pavement

No.	Life Cycle Stage	kg CO_2e/t	Total kg CO_2e
1-3	Material extraction and processing	52.88	203434.62
4	Transport to plant	36.52	140500.34
5	Asphalt production	47.83	83997.39
6	Transport to site	6.48	24946.30
7	Laying and compacting	4.70	18080.90
8	Project works	241.23	36184.10
9	Maintenance	34.27	5140.00
10	Reconstruction	15.89	61120.78
Stages 1-7 (3997 t material)		**148.42**	**637220.33**

The CO_2e emissions from the construction, maintenance and rehabilitation of road flexible pavements depend largely on how the required materials are extracted and processed, only the production of aggregates and asphalt being responsible for 1.2 million tons of CO_2 and consumption 705000 MWh in electricity and 43000000 MWh in 2009, broken down as shown in **Fig. 9** (Banes and Fifer, 2011).

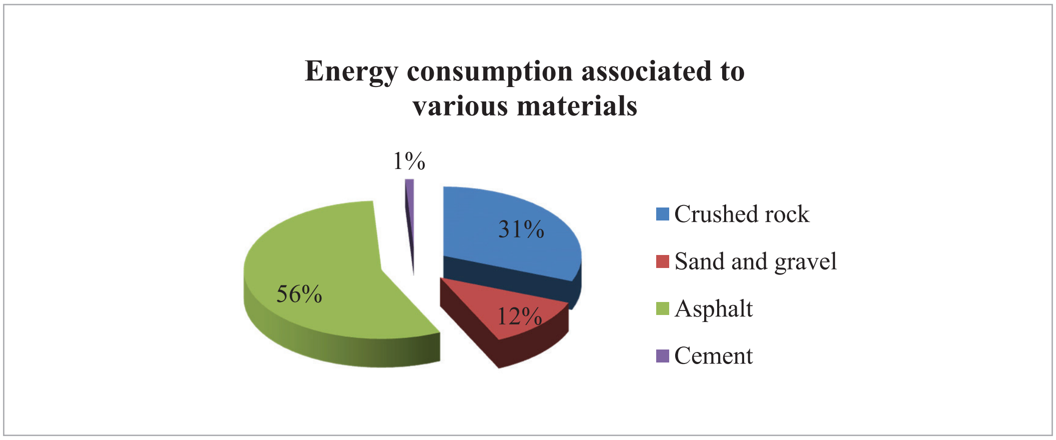

Fig. 9

Segmentation of energy consumption by main categories of aggregate (Banes and Fifer, 2011)

However, these amounts may decrease considerably if the aggregates excess water is reduced as the highest proportion of energy is consumed for drying and heating the aggregates. Another way the improvement the manufacturing process involves the use of recycled asphalt mixtures, resulting in reductions of up to 50% of emissions (Andrei, et al., 2014).

Analyzing the results research, performing a simple surface treatment implies the release into the atmosphere of an amount equal to 42760.33 kg CO_2e, its total cost being $ 3367 lane/mile and the service life increasing by 3.7 years.

The execution of thin layers leads to 56147.13 kg CO_2e, about 24% more than the previous strategy, but with an extension of 5.8 years. Execution costs are also higher than the simply surface treatment by about 65%.

Execution of slurry seal have as environmental impact the production of 23054.59 kg CO_2e (59% lower than for simple treatment and by 46% compared with thin layers). It extends the service life by 3.7 years, while the costs are $ 6398/lane/mile.

The highest increase in service life corresponds to heat planner and adding a 2.5 cm thickness layer, which represents 6.9 years. Nevertheless, associated costs and pollutant emissions are higher than in the first case ($ 8081/lane/mile and 53954.07 kg CO_2e).

In the case of construction of a new road pavement, in addition to the construction process of asphalt layers, it has been considered also the execution of surface dressing and retexturing in the frame of in-situ maintenance. Results of recent research undertaken have emphasized the need to apply intervention strategies at the appropriate time in order to prolong the road service life, because the alternative of constructing a new road pavement implies consumption of huge quantities of bituminous binders and non-renewable granular material simultaneously with the discharge into the atmosphere of an amount of 637220.33 kg CO_2e.

Discussions

The chains of causality associated to transport system assist in identify, monitor and assess all the environmental problems arising from the development of road networks. These chains can be a relevant instrument in decision making process and for comparative analysis of transport policies or technologies in order to select the optimal solution related to road projects, taking into account the urgent environmental aspects. The undertaken research also focused greatly on emphasizing environmental indicators specific to the analyzed chains of causality necessary in road field technique for quantifying and evaluating sustainability for current and future trends in the global concept of sustainable development.

Given that the most pressing environmental issue facing mankind consist in the effect of global warming and climate change associated with this phenomenon due to the increase concentration of pollutants in the atmosphere, the paper presents the results of recent research undertaken for the assessment of the environmental indicators associated with the construction of an asphalt road pavement, based on a Cradle to Grave approach, which includes all the stages of materials and energy production and all processes from raw material extraction, production, transportation and use phase of the products to their end of life. The Life Cycle Assessment Analysis was conducted on the entire built section of 1000 ml long and 7.0 m wide using a CRADLE TO GRAVE option, incorporated in the asPECT software.

Within this study five different intervention strategies performed for regular maintenance and structural reinforcement of a road flexible pavement have been analyzed in an environmental perspective as well as in an engineering approach. Regarding the ecological impact associated with road works the most ecofriendly strategy is represented by the execution of slurry seal, which will also extend the service life of the pavement with 3.7 years. Looking at the results under an engineering consideration, the optimal rehabilitation strategy to be applied consists in heat planner and adding a 2.5 cm thickness layer, the service life extension being in this case equal with 6.9 years, thus having a structural contribution. The worst case scenario studied in the frame of this research is represented by the reconstruction of a new pavement, when the specific intervention strategies haven't been applied when needed and the pavement condition of the road is poor, the user's safety being endangered. In this case the only viable solution is rebuilding the pavement, the ecological impact being significantly higher.

Additionally, to reduce the environmental impact of road infrastructure, a great importance is represented by the humidity of component materials, as the largest amount of energy is consumed in drying and heating of aggregates. According to recent studies, another way to streamline the manufacturing process implies the use of recycled asphalt mixtures, resulting in reductions of up to 50% the emissions.

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About the authors

CONDURAT MIHAELA

PhD Student

Technical University „Gh. Asachi" from Iasi, Romania, Faculty of Civil Engineering and Building Services, Department of Transportation Infrastructure and Foundations

Main research area

Impact assessment of road transport system. Measures regarding the prevention and reduction of ecological impact associated with road transport infrastructure

Address

Bulevardul Profesor Dimitrie Mangeron 1, Iași 700050
Tel. +40 745 409 930
E-mail: conduratmihaela@yahoo.com