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Life Cycle Assessment for Pavement Sustainable Development: Critical Review

Peyman Babashamsi
Universiti Kebangsaan Malaysia

Nur Izzi Md Yusoff
Universiti Kebangsaan Malaysia

Halil Ceylan
Iowa State University, hceylan@iastate.edu

Nor Ghani Md Nor
Universiti Kebangsaan Malaysia

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Abstract
Certainly, one of the most cost effective and comprehensive infrastructure assets of the build environment is road infrastructure. The environmental impacts of this asset during its lifecycle drive researchers to create a foundational framework to quantify these effects. Life cycle assessment (LCA), a method for the assessment of all modules in a life cycle, has been examined to evaluate all the environmental modules and components of road projects due to constraints of environmental assessments. The enthusiasm for enhancing the sustainable development of basic infrastructure leads to quick expansion on pavement life cycle assessment. An audit of applicable published LCA studies has recognized that environmental modules, such as the usage module (rolling resistance of pavement, carbonation, and albedo), end of life (EOL) module, and components such as traffic congestion during the construction module are not regarded in most of the articles. These modules potentially have the same environmental impact as other regularly considered modules such as materials, transportation, and construction. The goal of this study is to recognize shortfalls in the fields that bolster pavement LCA, to prepare a comprehensive and straight forward methodology, and to provide a basis on which related studies can move forward.

Keywords
sustainable development, Life cycle assessment (LCA), pavements, environment, and review

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LIFE CYCLE ASSESSMENT FOR PAVEMENT SUSTAINABLE DEVELOPMENT: CRITICAL REVIEW

Peyman Babashamsi [1,a*], Nur Izzi Md Yusoff [2,b], Halil Ceylan[3,c], Nor Ghani Md Nor [4,d]

[1,2]Department of Civil & Structural Engineering, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[3]Department of Civil, Construction and Environmental Engineering Iowa State University, Ames, Iowa 50011, USA
[4]Department of Economics and Management,Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[a]peymenshams@yahoo.com, [b]bizzi@eng.ukm.my, cchceylan@iastate.edu, [d]dnorghani@ukm.edu.my

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Abstract. Certainly, one of the most cost effective and comprehensive infrastructure assets of the build environment is road infrastructure. The environmental impacts of this asset during its life-cycle drive researchers to create a foundational framework to quantify these effects. Life cycle assessment (LCA), a method for the assessment of all modules in a life cycle, has been examined to evaluate all the environmental modules and components of road projects due to constraints of environmental assessments. The enthusiasm for enhancing the sustainable development of basic infrastructure leads to quick expansion on pavement life cycle assessment. An audit of applicable published LCA studies has recognized that environmental modules, such as the usage module (rolling resistance of pavement, carbonation, and albedo), end of life (EOL) module, and components such as traffic congestion during the construction module are not regarded in most of the articles. These modules potentially have the same environmental impact as other regularly considered modules such as materials, transportation, and construction. The goal of this study is to recognize shortfalls in the fields that bolster pavement LCA, to prepare a comprehensive and straight forward methodology, and to provide a basis on which related studies can move forward.

Introduction

There are always significant environmental and social impacts from road construction projects due to land use, energy and resource consumption, and transportation. Additionally, characteristics of roads such as geometry, structure, pavement surface index, and traffic delay during road activities impact energy use methods and emission levels [1]. Griffiths [2] categorized "environmental factors" in two groups. The first group consists of conventional related impacts like air pollution, water quality, variation of life forms (biodiversity), the design of the landscape and its aesthetics, as well as habitat and species protection. The second group comprises the new environmental impacts such as climate change, adaptation, efficiency in resource and material use, waste management, and the complicated boundary of sustainable development. An incomplete study in traditional environmental impact assessments is due to disregard of this complexity. Therefore, current studies have realized the necessity of an exhaustive LCA methodology for pavement activities to accelerate recognising of enhanced sets of sustainability indicators for the environment effects [3,4]. This can develop exhaustive strategies to mitigate emissions, waste, energy, water, and natural resource utilization.

Life Cycle Assessment (LCA)

LCA is a precise method used to compile and examine the inputs and outputs of materials and energy consumption and the related environmental impacts specifically attributable to the functioning of a product or service system throughout its life cycle [5]. In addition, LCA is defined as the "*consecutive and interrelated phases of a product system, from the acquisition of raw materials or the generation of natural resources until its final disposal*" by ISO-EN-UNE-14040 [6]. In the "cradle to grave" approach, the LCA of a pavement is separated into five distinctive modules, as indicated in Fig. 1: (1) raw materials and production, (2) construction, (3) usage, (4) maintenance and rehabilitation, and (5) end of life. Generally, flows of a product or system are isolated into: upstream (extract, process, transport and construct), service life (usage and maintenance), and downstream (deconstruct and disposal). Hereupon, environmental effects are computed based on energy use, waste generation, and other effects (i.e., global warming, ozone depletion, and acidification).

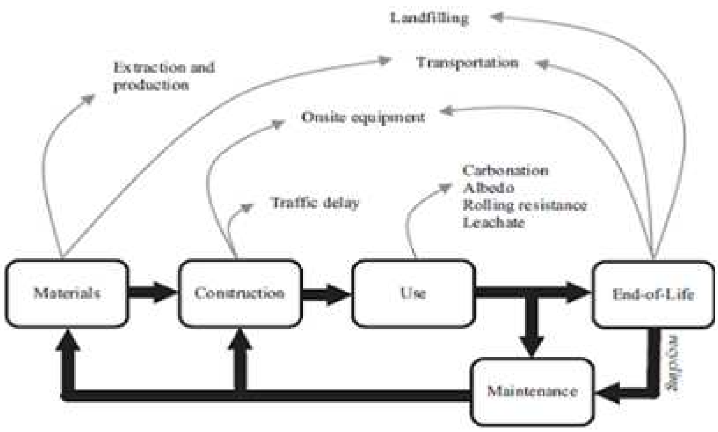

Figure 1: Modules and components of pavement LCA [3]

Consideration in LCA methodology. Some important decisions need to be taken under the goals and scope of a project. These decisions may be related to system boundaries, functional units, allocation methods, data quality and uncertainty, LCI, and LCIA scope. An absence of an agreement on the adequate functional unit to analyze pavements proves to be a real issue of the current pavement LCAs. If the functional unit is not reliable, then the results will differ despite the choice of system boundaries, impact factors, and different sources of variability are the same between the two studies [3].

When reviewing the LCA results, the allocation methods will come under the limelight [7,8]. Materials, such as asphalt from the refinery, are dependent on the co-product allocations as a variety of other oil products are extracted. Therefore, the environmental effects of the refinery will need to be divided amongst the various products. The amount of effects exerted should be considered in cases of materials such as concrete, when allocating any of the primary product or process. Allocations can be made based upon the physical or economic value of the products, as specified in the ISO 14040.

Another crucial point in LCA methodology is the quality of input data. The data available for the LCAs are not always of good quality, owing to the lack of validate data and reliability problems. The cement and the asphalt environmental factors available in the literature give the best example for the uncertainty present in the pavement LCA data. The accuracy of the environmental values of cement and asphalt are never examined in detail inside the current pavement LCAs, although they are major participants in the material extraction and production stage [9].

Numerous research consists of life-cycle inventories (LCIs) and do not expand to life-cycle impact assessments (LCIAs). However, LCIs are considered as stand-alone studies that are bolstered by the same ISO 14040 series guidelines that represent full LCA studies [6].

Previous studies. From 1996, since the first LCA study was published, the approach has persistently achieved attraction as a strategy to measure the pavement's environmental impacts. In 2010, Muench indicated that there are more trends in considering sustainability especially in road construction and operation [10]. Santero et al. [11] composed 15 road LCA studies (from 1996 to 2010) that were conducted in various countries, to clarify their system boundary levels. The study found that considering selected modules (material, construction, and maintenance) of the life cycle in a given analysis undermines the utility of the outcomes, as the omitted modules (use, end of life) regularly contribute to the general LCA and conceivably changed the determinations from a given study. After 2010, there was a revolution in sustainable development consideration, and the number of research on pavement LCA increased. The results of previous pavement LCA studies noted the majority of studies involved with different scopes and none attained a definitive objective of a genuine and comprehensive LCA. On the other hand, numerous studies take the guidelines, hypotheses, and expectations of LCA sufficiently enough to be considered in any event of incomplete pavement LCA.

The previously published road LCA studies are presented in Table 1. Despite some improvements, the vast majority of the latest LCA researches overlook modules such as usage, maintenance, and end of life. The deficiencies of the LCA studies are collected in the following sections to reach a subjective inference in developed pavement LCA.

Table 1: A list of published road pavement LCA studies with their system boundaries

Authors	Location	Analysis Period (years)	Life-cycle components in pavement LCA						
			Material Module		Construction Module		Usage Module	M&R Module	EOL Module
			Extraction & Production	Transportation	On-site Equipment	Traffic Congestion	Rolling resistance, Carbonation, Albedo, Leachate	Material & construction	Equipment, Transportation, Recycling
Hakkinen &Mekala (1996)	Finland	50	*	*	*	*	*	*	
Horvath & Henderson (1998)	US	10	*						
Rodebush (1999)	US	50	*		*			*	
Berthiaume & Bouchad (1999)	Canada	40	*					*	
Mroueh et al. (2000)	Finland	50	*	*	*			*	
Stripple (2001)	Sweden	40	*	*	*			*	
Nisbat et al. (2001)	US	40	*	*	*			*	
Park et al. (2003)	Korea	20	*		*				*
Chappat & Bilal (2003)	US	30	*					*	
Treloar et al. (2004)	Australia	40	*					*	
Zapata & Gambatese (2005)	US	10	*		*				
Hoang et al. (2005)	France	30							
Athena Institute (2006)	Canada	50	*	*	*			*	
Chan (2007)	US	n/a	*	*	*	*			
Marceau et al. (2007)	US								
Muga et al (2009)	US	35	*	*	*			*	
Huang et al. (2009)	UK	n/a	*	*	*	*			
White et al. (2010)	US	annualized	*	*					
Muench & Weiland (2010)	Different	50	*	*	*			*	
Zhang et al. (2010)	US	40	*	*	*	*	*	*	*
Santero (2010)	US	50	*	*	*	*	*	*	*
Sayagh et al. (2010)	n/a	30	*						
ECRPD (2010)	Different	25	*						
Cross et al. (2011)	US	n/a	*	*	*				
Cass & Mukherjee (2011)	US	50	*	*	*				
Tatari et al. (2012)	US	40	*	*	*				
Yu & Lu (2012)	US	50	*	*	*	*	*		
Ting et al. (2012)	US	30	*	*	*		*		
Bin Yu (2013)	US	50	*	*	*	*	*	*	*
Faisal Hameed (2013)	US	40	*	*	*			*	

(Darker rows were used in Santero et al. 2011)

LCA Research Gap

As indicated in Table 1, the material phase and the construction module are well archived in existing LCA studies. However, other phases and components are not well investigated by the researches. This paper serves to layout the present condition of knowledge with respect to the usage module, end of life module, and traffic delay (congestion) amid the life-cycle. Each module can be a possible critical contributor to the overall environmental impact and in this way they merit more particular consideration from LCA specialists.

Usage module. During operation, pavements collaborate with the environment impacts through rolling resistance, albedo, carbonation, and leachate. These effects are seldom involved in existing pavement LCAs, possibly due to the uncertainty and undeveloped supporting information. As shown in Table 1, only six out of 30 studies focused on the usage module. However, not all of the studies cover all the components. For instance, to appraise the just impact of rolling resistance on the LCA, Ting et al. [12] conducted case studies of various pavement maintenance and rehabilitation strategies. The study stated that the importance of rolling resistance is because of the effect on all vehicles utilizing the pavement. Another study by Chupin et al. [13] investigated around 12% of total fuel usage of vehicles related to pavement surface roughness and structural assets that are clearly rolling resistance subcomponents. Some other reasons, such as changing viscosity and stiffness of hot mix asphalt (HMA) under summer conditions can increase vehicles' fuel usage. Enhancing roughness makes more vibrations and reduces driving speed, which results in increased fuel consumption and emissions [4].

Carbonation is a common phenomenon that sequesters a segment of the CO2 that was initially freed from the limestone during cement production. The rate of carbonation fluctuated from 0.50 to 10 mm/$\sqrt{t}$ based on concrete components and the environment [14].The solar radiation absorbed by the pavement expands the encompassed temperature, leading to the urban heat island effect and increase usage of cooling gadgets in urban zones. Akbari et al. [15] expressed that each 0.01 increment in albedo can compensate 2.55 kg of transmitted CO2 for each m2 surface (radiative forcing). The same paper refers to a method that yields a higher balance of 4.90 kg of radiated CO_2 every m2 (urban heat island). Leachate is the substance drained from some pavement materials that may debase water quality and possibly represent a danger to drinking water. Azizian et al. and Marion et al. [16,17] reach conclusions that contaminants found in overflow makes from vehicular sources as opposed to pavement materials.

End of life module. Table 1 also shows that the end of life module (EOL) has been eliminated by most of the previous LCA studies. The pavement can be landfilled, recycled, or buried and became a supportive base layer for the next pavement structure. Each pavement requires a unique approach for quantifying the environmental impact. Ranjendran and Gambatese [18] claimed that EOL represents more than half the aggregate sum of waste produced over the life-cycle of a pavement. In addition, by recycling the toxicity (human beings) and eco-toxicity (other living species), as well as all other impact indices such as global warming potential (GWP), energy consumption, eutrophication, acidification, and tropospheric ozone formation will be decreased [19].

In regard to focusing on the level of waste generation and consuming resources from all over the world, the 'recycling' activity of the EOL module can be accounted as a high effect index to extend the utilization of recycled materials in next road projects and, therefore, resource protection for next generation. Some components, such as land and drainage cleaning components, which mostly include on-site equipment, have also been eliminated in previous studies.

Traffic delay. Closed lanes or lanes around construction sites usually creates queues and leads to traffic. The constrained data on traffic congestion and its importance within the pavement life cycle makes it hard to sum up its effect. At work sites on heavily-used routes, traffic delays can increase fuel use and emissions intensely [1]. Numerous economic models (e.g. the U.S. Environmental Protection Agency's MOVES [20]) are counting that gauge the cost of the delay, which is regularly measured by the quantity of cars delayed, measure of the time spent in lanes, and the value of time. These models can be adjusted to gauge environmental effects by coupling the outflows with proper emission factors and models.

DISCUSSION and RECOMMENDATION

LCA gives an important chance to limit the environmental impacts associated with a boundless and crucial infrastructure system. Enhancing the inadequacies in existing LCAs and supporting research fields will undoubtedly increase environmental performance and assist decision makers and stakeholders towards sustainability arrangements. To enhance LCA methodology this study prescribes:

- Consideration of a functional unit framework that accounts for significant characteristics of the pavement, including function, location, and design descriptions of system boundaries.
- Enhanced unification of LCA modules and components.
- Improved comprehension of the effect of each phase and stage in respect to remained life LCA.
- Improved reconciliation of sensible maintenance timetables and activities.
- Coherent and accepted accounting strategies for feedstock energy.
- Considering uncertainty on LCA results based on data and modeling errors.
- Sensitivity analysis for testing of outcomes to changes in variables.
- Coherent utilization of data quality scoring methods that account for general quality as well as for regional and temporal applicability.
- Enhanced energy use and emission factors for materials, especially for bitumen and cement production.
- Heightened utilization of LCIA to assess the environmental impact.
- More various utilizations of LCA than only comparisons of asphalt to concrete.
- Evolution of environmental emission and energy data particular to different regions.
- Consideration of distinctive electricity mixes, transportation distances, production variability, and other processes that vary between locations.

Conclusion

To encourage sustainable development of infrastructure assets and international focus on green road development, the verification of important environmental components is essential. By LCA evaluation (modules and components) the sustainable environment impact development can be reachable. Due to a lack of appropriate system boundaries, which can cover and support aspects of the LCA of a pavement project, the efforts are defeated. This review study works on previous LCA articles to recognize the levels of effect in different road LCA components through a qualitative evaluation. Regarding the study findings and the present researches of LCA, a comprehensive road system boundary is available. It is hoped that future studies with possible quantitate evaluation of various LCA modules will further enhance the model.

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