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Sustainability evaluation framework for pavement technologies: An integrated life cycle economic and environmental trade-off analysis

Adil Umer [a], Kasun Hewage [b,*], Husnain Haider [c], Rehan Sadiq [b]

[a] Project Delivery Branch - Construction, Alberta Transportation, Peace River, AB, Canada
[b] School of Engineering, University of British Columbia (Okanagan), Kelowna, BC, Canada
[c] Civil Engineering Department, College of Engineering, Qassim University, Buraydah, Qassim, Saudi Arabia

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ABSTRACT

Sustainability evaluation of pavement alternatives for given traffic loading and environmental conditions has always been a challenging task for pavement designers and managers. Pavement engineers and managers mainly use life cycle cost analysis (LCCA) to make a decision while the recent focus of academic research and regulatory agencies was more on the life cycle assessment (LCA) to evaluate the environmental impacts of different pavement alternatives. LCCA and LCA for more recent technologies, such as geosynthetics, have been relatively less addressed so far. Moreover, uncertainties due to inadequate data can also reduce effectiveness of the decision making process during the planning phase. In this research, an integrated LCCA and LCA framework is developed for sustainability evaluation of different pavement alternatives based on an integrated economic and environmental trade-off analysis. The framework can effectively evaluate different pavement technologies, including flexible, concrete, geosynthetics, and their combinations under different subgrade characteristics and traffic conditions. The fuzzy composite programming (FCP) is used: (i) to deal with the uncertainties associated with limited data and vagueness in experienced judgment, (ii) to integrate the results obtained from LCCA and LCA, and (iii) for final ranking of pavement alternatives. For final selection, decision makers can trade-off between cost and environmental impacts over the life cycle of the pavement alternative. The study results indicate that geosynthetics can be used to enhance the pavement service life for low volume roads with optimized cost and minimum environmental impacts.

1. Introduction

The construction and maintenance of municipal pavements necessitate substantial budget, natural resources, and human capital. According to the Canadian Municipal Infrastructure Report Card (2012), municipal roads have the highest proportion in poor condition (20.6%) as compared to other infrastructure systems, i.e., drinking water (2.0%), wastewater (6.3%), and storm water (5.7%). Innovative pavement design and maintenance strategies are being developed to achieve long-term per-

* Corresponding author.
E-mail addresses: adil.umer@gov.ab.ca (A. Umer), kasun.hewage@ubc.ca (K. Hewage), husnain.haider@alumni.ubc.ca (H. Haider), rehan.sadiq@ubc.ca (R. Sadiq).

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formance and sustainability goals. Earlier, these goals mainly focused on initial and maintenance costs. In more recent years, due to the growing awareness about natural resources conservation and ecological degradation, the goal for environmental sustainability has also been given significant importance in the decision-making process.

Sustainability evaluation of pavement alternatives is a challenging task for pavement designers and managers (Holt et al., 2011). Pavement alternatives such as asphalt or concrete pavements differ in type, extent, and timing of maintenance and rehabilitation (M&R) activities needed as they offer different level of resistance to environmental degradation and traffic loadings. In general, asphalt pavements have lower construction costs but deteriorate rapidly as compared to rigid pavements that have higher initial construction cost. Geosynthetically reinforced flexible pavement (GRFP) is relatively a more recent development in which geotextiles are used either to increase the service life of pavement or to reduce the earthwork required during highway construction. Therefore, a decision has to be reached regarding the use of geotextiles i.e. whether to strengthen pavement structure or reduce requirement of base course material? The process becomes more complex when environmental impacts are also considered in the overall decision making process. For example, a sustainable alternative may have higher cost initially but its environmental impacts and maintenance costs may be reduced over its life cycle, in contrast to an alternative whose life cycle costs are known while associated environmental implications are unknown. Economic and environmental trade-offs analysis for sustainability evaluation of pavement alternatives may resolve this problem.

The methodologies for economic and environmental evaluation are termed formally as life cycle cost analysis (LCCA) and life cycle assessment (LCA) respectively. Environmental assessment of pavements is mostly an area of interest for academic research, while in the industry, 'costs' serve as the primary factor to compare pavement alternatives. Uncertainties are inevitable in LCA-LCCA studies because of the extent of vagueness involved in human reasoning while judging the inputs from limited and imprecise information available in the planning phases of projects. Some of the key factors contributing to uncertainty in conducting pavement LCCA and LCA studies include the inability to project accurate costs for construction and maintenance, pavement performance, and the timing and extent of M&R activities needed during the life cycle of pavements (Atkinson et al., 2006; Noshadravan et al., 2013; Swei et al., 2013; Yoe et al., 2010; C-SHRP, 2000; Hajek et al., 2004; Peshkin and Hoerner, 2005; Walls III and Smith, 1999).

Several studies have been conducted in the past to evaluate sustainability of pavements in terms of life cycle costs and/or environmental impacts. Detailed literature review of these studies is out of scope of this paper; however, some of the relevant studies carried out in the recent past are briefly outlined here. Most of the studies were conducted on LCA for asphalt pavements (Santos et al., 2015; Celauro et al., 2015; Rodríguez-Alloza et al., 2015; Turk et al., 2014; Vidal et al., 2013). Anastasiou et al. (2015) recently performed LCA for concrete pavements, and Yu and Lu (2012) compared the life cycle costs of concrete and asphalt pavements. Giustozzi et al. (2012) carried out both the LCA and LCCA for asphalt pavements only. Recently, some researchers evaluated concrete and asphalt pavements using both the LCA and LCCA (Liu et al. 2015; Chen et al. 2015). Yang (2006) evaluated the effectiveness of geotextiles in flexible pavements through LCCA. However, none of these studies took the abovementioned uncertainties into account. Noshadravan et al. (2013) performed LCA for the conventional types of pavements and included uncertainties in their evaluation as well; and Swei et al. (2013) included uncertainties into account in their LCCA study for asphalt pavements. In these studies, the conventional pavement types were either evaluated on the basis of cost or their environmental impacts. The results (i.e., selected pavement alternative) could be misleading when the evaluation is carried out without integrating the results of both the LCA and LCCA.

To the best of our knowledge, there is no comprehensive sustainability evaluation framework developed, so far, which addressed uncertainties in raw data during the planning phases and at the same time integrate LCA-LCCA results to compare different pavement alternatives, including asphalt, concrete, and geosynthetics. Generally, probabilistic methods are used to solve the problem of uncertain inputs; however, such methods are computationally complex and require significant data which generally in not available during the planning phase. Moreover, the uncertainties, such as approximate reasoning, limited data, unclear information etc., can be more effectively addressed with the application of fuzzy set theory (Dyck et al., 2014; Reza, 2013).

The main objective of this paper is to integrate life cycle cost and environmental impacts of alternative pavements while considering uncertainties to assist more sustainable decision-making. This study not only considers asphalt and concrete alternative but also includes GRFP in the form of two competing alternatives where geotextiles either increase service life or reduce base course material. Fuzzy composite programming (FCP) technique is used to generate and integrate the results from LCA and LCCA for the alternatives under uncertainty. This study attempted to close the gap between academic research (where latest focus is on life cycle assessment) and practical decision making (where main focus is on costs) with limited attention to uncertainties for sustainable selection of pavements.

2. Methods

2.1. Pavement sustainability evaluation framework

In this paper, economic and environmental life cycle evaluation is conducted for three types of pavements, i.e., rigid, flexible and geosynthetically reinforced flexible pavements. The overall sustainability evaluation framework is shown in Fig. 1. Windows Pavement Analysis Software (WinPAS) developed by American Concrete Pavement Association (ACPA) based on