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Review

Environmental assessment of pavement infrastructure: A systematic review

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ABSTRACT

Through a critical review and systematic analysis of pavement life cycle assessment (LCA) studies published over the past two decades, this study shows that the available information regarding the environmental impacts of pavement infrastructure is not sufficient to determine what pavement type is more environmentally sustainable. Limitations and uncertainties related to data, system boundary and functional unit definitions, consideration of use and maintenance phase impacts, are identified as the main reasons for inconsistency of reported results in pavement LCA studies. The study outcomes also highlight the need for advancement of knowledge pertaining to: (1) utilization of performance-adjusted functional units, (2) accurate estimation of use, maintenance, and end-of-life impacts, (3) incorporation of the dynamic and uncertain nature of pavement condition performance in impact assessment; (4) development of region-specific inventory data for impact estimation; and (5) consideration of a standard set of impact categories for comparison of environmental performance of different pavement types. Advancing the knowledge in these areas is critical in providing consistent and reliable results to inform decision-making toward more sustainable roadway infrastructure.

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1. Introduction

Pavement infrastructure plays an important role in the sustainability of urban systems (FHWA, 2011). Pavement types can directly affect fuel consumption and motor vehicle emissions. In 2011, there were approximately 253 million registered vehicles, including passenger cars, light trucks, vans, and utility vehicles (FHWA, 2014). Vehicles consumed about 168,597,250 thousand gallons of fuel, mainly gasoline, which accounted for half of all gasoline used in the U.S (TRB, 2006). The transportation sector as a whole is responsible for 27% of greenhouse gas emissions in the U.S (EPA, 2015b). Pavement infrastructures are important components of surface transportation and have significant environmental impacts. Understanding the environmental impacts of pavement infrastructure is essential for enhancing the sustainability of transportation systems.

Life cycle assessment (LCA) has been utilized over the past two decades in order to estimate environmental impacts of pavement in infrastructures. The use of LCA has gained attention in environmental assessment of various products and processes since the 1980s. However, unlike processes and services in other industries, LCA is still in the early stage of application in infrastructure systems (Harvey and Meijer, 2014). The first LCA study in the pavement infrastructure was conducted by Roudebush (1996). Wilfred H. Roudebush was commissioned by the Portland Cement Association in 1996 to conduct an Environmental Value Engineering (EVE) life cycle assessment for concrete and asphalt highway pavement systems (Roudebush, 1996). This study was recognized as one of the original LCA publications related to pavement infrastructure. In the same year, Finnish researchers, Häkkinen and Makela (1996), conducted a LCA study on both asphalt and concrete pavements. The first peer-reviewed journal on LCA was published by Horvath and Hendrickson in 1998 (Santero et al., 2010c). At the beginning of the 2000s, life cycle analysis of pavement infrastructure started to gain more popularity. Not only in the U.S., but also in Europe, Canada, Australia and South Korea, LCA was utilized in practice to design and select pavement types (Cormier and Thébeau, 2003; Ventura and Jullien, 2009). Over the past decade, more scholarly publications appeared in the literature (Santero et al., 2010a). Furthermore, inventory data and tools, such as PaLATE, PE-2, Economic Input-Output Life Cycle Assessment (EIO-LCA) have been developed to enable pavement life cycle analysis (Facanha and Horvath, 2007; Mukherjee et al., 2013).

The main focus of the existing pavement LCA studies over the past two decades has been on comparison of asphalt and concrete pavements. In fact, there has been efforts/movements among scientists and practitioners to evaluate the environmental impacts of asphalt and concrete pavements and introduce one as the sustainable pavement type. Despite the growing literature on pavement LCA, there is no consensus regarding what pavement type has superiority in terms of environmental performance. The objective of the study presented in this paper is to verify whether the existing information in the literature is sufficient to determine what pavement type has less environmental impact. To this end, a comprehensive and critical review of the existing studies published over the past twenty years, directly related to pavement LCA, was conducted. The following section explains the research scope and framework.

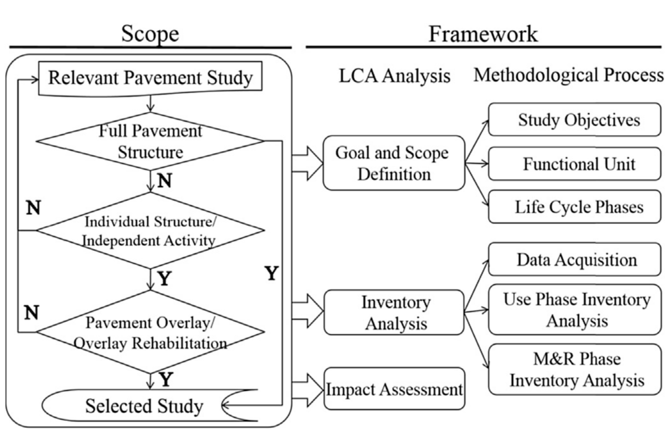

Fig. 1. Scope and framework.

2. Research frameworks and scope

Studies related to pavement LCA studies published between 1996 and 2015 were reviewed in order to provide a critical analysis of current methods, data, tools, knowledge and limitations. The scope of this study (Fig. 1) focuses on environmental impacts related to roadway and pavement structures (excluding non-pavement overlay structure, such as subbase and base components). Thirty-two studies (summarized in Table 1 and Table 2) related to pavement LCA were identified and analyzed. Among the studies identified, only one involved a critical review of pavement LCA. This study is one of the very first efforts to critically analyze the limitations in the pavement LCA literature in order to inform future research directions. The only other critical review of pavement LCA was conducted by Santero et al. (2011). This study considers emerging research areas in pavement LCA studies such as assessment of pavement vehicle interaction (PVI) and vehicle emissions during use phase. Also, this study presents an in-depth comparison of findings of pavement LCA studies in order to highlight the knowledge gaps. Figs. 2 and 3 provide an overview of the pavement LCA studies reviewed in this paper, based on the year and location of studies and LCA approaches used. These studies were reviewed through the lenses of the framework shown in Fig. 1. The identified studies were screened to identify the ones with full pavement structure scope. Studies that investigated individual elements (e.g., study of pavement recycling or cement type) as well as individual processes (e.g., study of pavement overlay methods) were excluded. The final pool of selected studies were analyzed based on the adopted LCA steps as well as methodological processes. The framework includes LCA steps and the methodological processes used in each step. Through this analysis, the findings and limitation of all previous studies were identified and evaluated in order to highlight directions for future research.

3. Pavement LCA

The existing studies have conducted pavement LCA through the use of three approaches: (1) input-output LCA; (2) process LCA; and (3) hybrid LCA, which is a combination of input-output and process approaches. Input-Output LCA (IO-LCA) is an environmental variation from the economic model input-output method developed by Wassily Leontief in 1936 and was first proposed for environmental assessment by Horvath and Hendrickson (1998). The IO-LCA is a top down approach that encompasses the entire supply chain of a product in different environmental sectors. IO-LCA analyzes all sectors of the economy by identifying the flow of goods and services between different sectors involved in producing a unit of output from a given sector. The outputs in the IO-LCA include energy, global warming potential (GWP), and CO_2 emissions.

Process LCA is an environmental analysis approach that quantifies the inputs and outputs of every process identified within the system boundary of a given product or service (Santero et al.,

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