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Greenhouse gas emissions of alternative pavement designs: Framework development and illustrative application

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ABSTRACT

Pavement rehabilitation is carbon intensive and the choice of pavement type is a critical factor in controlling greenhouse gas (GHG) emissions. The existing body of knowledge is not able to support decision-making on pavement choice due to a lack of consensus on the system boundaries, the functional units and the estimation periods. Excessive data requirements further inhibit the generalization of the existing methodologies for design evaluation at the early planning stage. This study proposes a practical life-cycle GHG estimation approach, which is arguably effective to benchmark pavement emissions given project bid tabulation. A set of case studies conducted for this study suggest that recycled asphalt pavement (e.g., foam stabilized base (FSB), and warm mix asphalt (WMA)) would prevent up to 50% of GHGs from the initial construction phase. However, from a life-cycle perspective, pavement emissions are dictated largely by the traffic characteristics and the analysis period for the use phase. The benefits from using recycled materials (e.g., FSB) are likely to diminish if the recycled products do not perform as well as those properly proportioned with less recycled materials, or if the recycled materials are locally unavailable. When the AADT reaches 10,000, use phase releases more than 97% of the life cycle emissions and the emissions difference among alternative designs will be within 1%.

1. Introduction

The construction and maintenance of a pavement network is a carbon-intensive process. Nearly 17 million metric tons (MT) of greenhouse gas (GHG) is emitted from pavement-related activities, making it the second largest construction-related emission contributor after residential and commercial buildings (Truitt, 2009). This fact motivates state and local transportation agencies to investigate strategies that reduce the GHGs using environmentally sustainable engineering practices. Several past studies have used actual construction site data to support efforts toward reducing emissions due to on-site activities (e.g., Miller-Hooks et al., 2010; Truitt, 2009; Huang et al., 2009). However, the optimization of pavement designs rather than on-site activities is believed to be a more efficient strategy for two reasons. First, the construction materials selected during pavement designs account for approximately 80% of the total emissions from a typical project. Increasing the proportion of recycled materials may result in a 27% GHG mitigation, while improving equipment efficiency saves only 12% (Australia, 2008; Miller-Hooks et al., 2010). Second, the pavement design impacts the construction process, the usage of equipment and the upstream material production. For example, using a foam stabilized base (FSB) eliminates the need to quarry and transport virgin aggregates, and reduces the asphalt content by 60% compared to the conventional hot mix asphalt (HMA). Given this potential for significant savings, the challenge is to propose a methodology that enables decision makers to accurately measure and discriminate the GHG emissions for alternative pavement designs.

GHG emissions from alternative pavement designs have been evaluated using LCA for over a decade (Santero and Horvath, 2009). The LCA assesses the pavement and explores the environmental impacts over its entire life cycle: from site preparation, raw material extraction and transportation, installation and renovation to facility operation and demolition. Most of the past studies focused on the projects that have been delivered, and derived some general conclusions about the design comparisons, often asphalt versus concrete, based on the historical performance data (e.g., ASTAE, 2011; Huang et al., 2013; Mukherjee & Cass, 2011; Cass & Mukherjee, 2011; Meil, 2006; Häkkinen & Mäkelä, 1996).

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However, given the unique nature of the construction process and the site conditions at each project, general conclusions derived from historical observations may not be applicable for new pavement projects in the planning stage. Even within pavements of similar designs (e.g., HMA reconstruction), the estimated GHG range from 92 MT to 291 MT per lane-kilometer (km) (Mukherjee & Cass, 2011).

The main objective of this study is to develop a framework for the estimation and comparison of GHG emissions from roadway rehabilitations using portland cement concrete (PCC), HMA, warm mix asphalt (WMA) and FSB. Cradle to grave assessment principle is followed, which takes into account all life cycle stages from raw material extraction up to the point at which it reaches end of life. Since differences in structural performances of pavement materials can have strong influences on the quantities of material usage, the carbon intensity per unit of structural capacity (CIS) is introduced to offer comparisons between flexible pavement using HMA, FSB and WMA. This research also describes a way to measure emissions in terms of the bid items (construction tasks) by developing the inventories of materials and equipment. It eliminates the need to observe on-site activities and enables the GHG estimation at the early design phase of a pavement project. The results can be valuable to designers and contractors who want to benchmark their designs and construction options, state and local agencies that are increasingly mandated to improve their environmental friendly engineering practices, and researchers who identify ways of improving construction designs and processes that reduce long-term GHG emissions.

2. Literature review

LCA is typically used to examine the environmental impacts of different activities that occur during the life cycle of the pavement. The International Organization for Standardization (ISO) developed the ISO 14040 series publications (14040: 2006, 14044: 2006, 14047: 2003, 14048: 2002), which include an international standard on GHG accounting and reporting for project products (ISO, 2006). In practice, the ISO standards are supplemented by the GHG reporting protocols from the World Resources Institute (WRI) (2005), the Publicly Available Specification (PAS) 2050 (2011), the Climate Registry (TCR) (2008) and the European Network of Construction Companies for Research and Development (ENCORD) (2010). These protocols specify the requirements for the assessment of the life cycle emissions, and serve as a reference for current estimation models/tools. Existing studies that are summarized in Fig. 1 establish additional principles and techniques that address the scope, procedure and data requirements of GHG assessment. However, given the inevitable time, data and knowledge constraints, most of the past pavement LCA studies have been forced to simplify the scope and use the data specific to particular locations (Santero et al., 2010). As a result, there is a lack of agreement between results in the existing body of pavement LCA research. This disagreement is largely due to the variable estimation methodologies/analysis boundaries, the inconsistent pavement designs and functional units, and the incomplete available data for existing pavement LCA models/tools.

While the emissions from pavement materials are considered in each study, other emission contributors such as site preparation and traffic delays are often excluded to cater to the specific purpose of an LCA. The site preparation includes potentially significant components such as carbon stock changes attributed to the removal of biomass, dead organic matter and soil. Kim et al. (2012) and Miller-Hooks et al. (2010) attempt to use absolute carbon loss to quantify net GHG emissions from site preparation. Their studies may overestimate carbon efflux because they ignore the fact that biomass products and landfills serve as reservoirs of carbon and prevent carbon from being released into the atmosphere. In addition to site preparation, traffic delays arising from the lane and road closures, which are often omitted from current studies, produce substantial amount of GHGs due to the extra fuel consumption from idling cars, as reported in the studies of Mukherjee and Cass (2011), Harvey et al. (2010), Huang et al. (2009), Chan (2007) and Häkkinen & Mäkelä (1996). Several software packages have been developed to estimate traffic delays including both slowdowns and queues, as presented in Fig. 1. None of them are particularly designed for or applied for estimating the GHG emissions associated with the delay. Therefore, the disparity of current emission estimation suggests that narrowly defined estimation methodologies generally leads to large underestimates of GHG emissions, as noted by Horvath and Hendrickson (1998), Stripple (2001), Zapata and Gambatese (2005) and Hendrickson et al. (2006).

Existing studies tend to compare GHG emissions from constructing one lane-km roads using the unit of metric ton carbon dioxide equivalents (MT CO_2e) per lane-km. This comparison exists potential defects given the fact that structural layers vary by different traffic demands and locations (Santero et al., 2010). For example, Cass and Mukherjee (2011) examined an 28 centimeter (cm) (11-inch) asphalt layer on a 10 cm (4-inch) open graded granular base carrying 17,900 vehicles per day in Michigan that released 436.9 MT CO_2e per lane-km due to material production; Huang et al. (2013) investigated a 18 cm (7-inch) asphalt layer over an 20 cm (8-inch) cement stabilized base over a 25 cm (10-inch) stabilized foundation carrying 25,300 vehicles per day in the United Kingdom that produced 143.0 MT CO_2e per lane-km from material production. These examples are two pavement projects with dramatically different structures, locations and design traffic requirements. Simply taking length as the unifying functional unit (e.g., MT CO_2e per lane-km) is not sufficient. A more relevant functional unit would need to include, at a minimum, the same pavement structure and traffic characteristics.

In principle, an LCA will examine in detail all anticipated sources of emissions (e.g., material and equipment), across all relevant environmental-influenced categories. However, in reality, it would be too difficult for the reporters to obtain these data and strong assumptions have to be made, which may result in the omission or misrepresentation of significant emission sources. Kim et al. (2012) proposed a framework allowing users to easily predict emissions based on the information available during the feasibility study phase. Yet Kim et al. (2012) only focus on materials production and construction phases of asphalt pavement. Inclusion of other phases or pavement types may require approaches that are fundamentally different from the proposed framework.

3. Pavement types and estimation principles

3.1. Alternative pavement designs

Most hard surfaced pavement types can be divided into two categories, rigid and flexible. A rigid pavement structure is composed of a PCC surface slab and underlying base and sub-base layers (if used) (Russel and Lenz, 2011). Flexible pavements are constructed with a bituminous (or asphalt) bound surface over one or more unbound base courses. Flexible pavement can be placed into one of the following categories based on the layer bituminous material:

HMA is the most common flexible pavement type in the United States. HMA consists of a mixture of aggregate and liquid asphalt cement, which are heated and mixed at a temperature above 300 °F.