Environmental Life-Cycle Assessment for Asphalt Pavements: Issues and Recommended Future Directions

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ABSTRACT: Life-Cycle Assessment (LCA) analyzes the total energy and resource requirements and environmental impact of human-designed systems. Both policymakers and industry have shown a great deal of interest in applying LCA as a decision-making criterion during planning and design for new pavement construction, and maintenance and rehabilitation activities. This interest results from two different perspectives: first, from recognition that pavement activities have effects on the environment, which must first be evaluated before they can be minimized to improve pavement system sustainability; and second, from a perception that competitive advantage can come from "green marketing" through improved pavement sustainability. This paper provides a brief overview of LCA and identifies the most important unresolved issues and gaps in the application of LCA to pavements. Based on this review, recommendations are made for improving the scientific viability of LCA when applied to pavements, including how to implement pavement LCA and key research needs for improving its validity and accuracy.

KEY WORDS: Life-cycle assessment, pavement, asphalt concrete, global warming, policy

1 INTRODUCTION

As sustainability ideals continue to be promoted by social and political agendas, transportation agencies and the pavement industry face a growing need to measure and then reduce their environmental footprint. Although these organizations are driven by different forces (transportation agencies through legislative benchmarks and the pavement industry through competitive advantage), both require the knowledge and tools to meet their specific objectives. However, the need for answers often outpaces the state of the knowledge, which produces a gap between what is practiced and what is understood. The repercussions of such imbalance are manifested in ill-advised policies where conclusions are drawn based on incomplete science. These gaps are serious enough that supposedly "green" solutions may actually produce net negative impacts on the environment. In order to avoid such quagmires, the state of the science needs to be improved so that the environmental impacts are appropriately quantified. This paper explores how the use of life-cycle assessment (LCA) can contribute to sustainability efforts and discusses unresolved issues within the framework that need to be addressed.

1.1 Brief Overview of LCA

LCA is an environmental assessment approach that measures the inputs (e.g., energy, resources) and outputs (e.g., air emissions, water releases) to a system over its life cycle. The goal is to capture the environmental impacts from a cradle-to-grave perspective by determining the impact from each life-cycle phase. In context to pavements, this means that impacts result not only from the extraction and production of paving materials, but also occur during their construction, use, maintenance, and end-of-life processes.

The principles and procedures for conducting an LCA are outlined in the ISO 14040 family of international standards (ISO 2003; ISO 2006a; ISO 2006b). The standards identify four stages of the assessment procedure: goal and scope definition, inventory analysis, impact assessment, and interpretation. Some studies choose to bypass the impact assessment stage of the LCA methodology based on the needs of the study. These studies, known as life-cycle inventories (LCIs) are still recognized as standalone projects and follow the same basic approach as a full LCA.

While these standards provide general guidance on how to perform an assessment, they offer little information for a particular product or system. As a result, many project-specific issues, such as scoping and allocation protocols, need to be determined on a case-by-case basis. For pavements, the ISO standards provide no specific information regarding what phases and components to include in the life cycle, what analysis period to use, or where to locate appropriate data. It would be unreasonable to expect this level of detail from a generalized standard that applies to countless products and services. However, this lack of detail means that many parts of the LCA process are subject to the interpretation of the practitioner, resulting in assessments on identical systems that arrive at different, even conflicting, conclusions. Many of the challenges associated with LCA are focused on resolving those inconsistencies through better research and discussion and eventual consensus regarding appropriate practice that effectively quantifies environmental impacts.

1.2 Extent of Existing Pavement LCA Research

Pavements were first analyzed using LCA in the late 1990s (e.g., Häkkinen and Mäkelä 1996; Horvath and Hendrickson 1998). Since then, studies have been published through a variety of outlets, including industry organizations, academic institutions, and peer-reviewed journals. The scope of many of these studies is comparison of asphalt pavements to concrete pavements in an attempt to identify which material is the most environmentally friendly. Overall, there is little consensus amongst the literature as to which material wins the debate. For example, whereas Stripple (2001) found that asphalt pavements require less process energy than do concrete pavements, Athena (2006) comes to the opposite conclusion (Stripple 2001; Athena Institute 2006). The pervasiveness of these contradictions can be traced back to real differences in the performance of materials and designs, as well as differences due to inconsistencies between study methodologies (e.g., differing scopes and accounting procedures), dissimilar data sources, and disparate functional units.

Another telling aspect of the existing literature is the metrics by which environmental impact is measured. Virtually all studies consider energy consumption, and many add both conventional and greenhouse gas air emissions. However, assessments rarely inventory other environmental metrics, such as water pollution and water consumption. The consequence of this limitation is that pavements are assessed and compared using only a portion of what constitutes their environmental impact. Moreover, most studies fail to perform comprehensive impact assessments, making it more appropriate to classify them as LCIs rather than complete LCAs.

2 ISSUES RELEVANT TO THE ASPHALT PAVEMENT LIFE CYCLE

The following sections discuss two issues relevant to the pavement life cycle: inclusion of the applicable life-cycle phases and proper accounting for the feedstock energy in bitumen. Best-practice approaches for each issue are recommended based on the individual evaluation.

2.1 Inclusion of Applicable Life-Cycle Phases

An LCA should capture all relevant processes throughout the life cycle of the product or system under study. However, the system boundary and scope of a study is often curtailed due to limited data availability, unavoidable modeling assumptions, or incomplete understanding of the product or system under study. These limitations have potentially serious consequences, since the omission of life-cycle components may introduce bias into the results of an LCA. Such bias can lead to unfounded conclusions and flawed environmental policies.

Existing pavement LCAs tend to be constrained by limited system boundaries. The inputs and outputs tracked in an LCA are typically associated with the extraction and production of paving materials, the transportation of those materials, and the heavy equipment needed to transform the materials into a pavement. However, these activities comprise only a fraction of the pavement life cycle. In particular, traffic delay during construction activities, the use of the pavement (i.e., how the pavement affects fuel consumption and the environment while in place), and end-of-life activities are routinely not accounted for within the assessment framework. Research has shown that these components are often important (or even dominant) contributors to the overall life-cycle impact of a pavement (Santero and Horvath 2009), so their omission has potentially serious consequences on the results.

Depending on the scope and objectives of a study, not all of the components need to be considered. For consequential LCAs (studies which assess changes to a system (Curran 2006)), some features may be identical between the compared products, making any environmental impact differences associated with that feature insignificant. Using albedo as an example, the comparison of two similar asphalt pavements may have the same average albedo over their lifetime, thus making irrelevant any impact difference from the urban heat island effect or from radiative forcing. Similar situations exist for the other components where their omission can be justified after evaluation of the study parameters. This exclusion rationale cannot be used for attributional LCAs, which attempt to describe the entire footprint of a product (Curran 2006).

The method by which components are quantified may also vary based on the accuracy of the supporting data. This is epitomized by the large uncertainties regarding the effect of a pavement on fuel consumption. The roughness and structure of the pavement are known to affect fuel consumption (e.g., Sime and Asmore 2000; Taylor and Patten 2006), but a definitive model calculating that effect is not yet available. The best information is still empirical and generally not comprehensive in nature and should not be relied upon for exact calculations. However, as mentioned before, choosing to exclude this component because of uncertainty introduces bias into the LCA results. Instead, in situations where exact numbers are unable to be determined, sensitivity analyses can be used to test the robustness of conclusions. Alternatively, if ample statistical data is available, stochastic uncertainty analyses can be employed to test the robustness of the conclusion. Either way, this allows all relevant components to be included, even if the best estimate of its value is uncertain.

2.2 Accounting for Feedstock Energy

The energy consumption associated with a material is often broken up into different components. Expended (or process) energy refers to the energy used throughout the supply chain to produce a material. Feedstock energy refers to the calorific energy inherent in material and is typically analogous with the thermodynamic heating value. For most LCAs that compare total energy (or total primary energy) for two systems, expended energy and feedstock energy are combined or presented together in graphical representation and reporting. The typical interpretation is that, all else equal, the system requiring less energy is "better" than the one requiring more.

In terms of energy conservation or efficiency, the validity of including feedstock energy is not entirely straightforward. Feedstock energy could be viewed as a benefit or as a lost opportunity. For example, bitumen could be interpreted as a material that stores fossil energy. During storage we derive a benefit from its properties as a material, but theoretically could use the material as an energy source after its application as a material has run its course.

While the ISO 14044 standard unambiguously requires the tracking and reporting of feedstock energy in an LCA's energy inventory, this metric may not be suitable or meaningful when applied to asphalt pavements. Bitumen (also referred to as asphalt or liquid asphalt) is the binding agent in asphalt concrete. It is a residual product from the crude oil distillation process, and as such has a significant amount of energy (40.2 MJ/kg) (IPCC 2006) stored in it. To put this in perspective, diesel fuel has an energy content of about 45.8 MJ/kg. In contrast to the feedstock energy in bitumen, the energy expended to produce bitumen is quite low, approximately 0.4 to 6 MJ/kg (Zapata and Gambatese 2005).

Despite the high energy content in bitumen, it has not been widely used as a fuel. Applications exists (e.g., specialty boilers, cement kilns) that are able to combust bitumen, but the resulting emissions include high levels of pollutants (Faber 2002), which is not surprising as it includes impurities left over from the refining process. At many refineries, the functionality exists to upgrade bitumen to lighter fractions (and hence, more ubiquitous fuels) through catalytic cracking, but the upgrading process comes at a heavy energy cost.

Once used as a binder in asphalt pavement, energy recovery from bitumen is even more difficult since it is mixed with aggregates and other materials. In the future, new refining technologies may be available to recover a portion of the bitumen in asphalt pavements, making a portion of the feedstock energy accessible for useful work and diverting it from its use as a binder for asphalt. Because technologies will continue to change over time, as may the acceptability of using bitumen as a fuel, any estimate of useful or recoverable energy from bitumen will be temporally and even geographically dependent.

Following this line of reasoning, we might also consider whether to report feedstock carbon content. If an impact of concern is CO_2 emissions or global warming impacts, bitumen could be interpreted as a mechanism for carbon storage which would, potentially, become CO_2 through combustion if bitumen was used as an energy resource rather than a pavement material. Moreover, combustion of bitumen emits considerably more CO_2 per unit energy than other petroleum sources (Herold 2003). While we are not advocating for reporting feedstock carbon content, this example highlights the problem of interpreting feedstock energy.

Frischknecht et al. (1998) recommend that mass flows of materials be tracked in the life-cycle inventory stage of LCA, but not energy flows (Frischknecht et al. 1998). The basis for this recommendation is that any useful interpretation of energy within the mass flow of a primary resource is mediated by technology and human values. The effects of technologies and human values should be addressed in the impact assessment stage of LCA, not the inventory which should be independent of these changing variables. Frischknecht et al.'s logic is quite reasonable, particularly in the context of bitumen feedstock energy. Best available technology (BAT) determines the usefulness of feedstock energy contained in a material, assuming that energy recovery (or foregone/delayed energy consumption) is our reason for tracking feedstock energy. This approach provides an inventory of material flows that can be reinterpreted at a later date if necessary, but also provides a clear and meaningful interpretation of what feedstock energy actually means based on our current technologies.

A shortcoming of this method is that the system boundary of the study becomes hazy. In the case of bitumen, feedstock energy and recoverable energy could be reported in the impact stage of LCA, but the pollutants emitted during its combustion would not be reported. Energy recovery either does or does not occur. If it does occur as part of the end-of-life stage for bitumen, then the emissions associated with it should be reported. If it does not, then the feedstock energy will remain in the bitumen. For either fate, reporting recoverable energy without its associated impacts and emissions seems to unacceptably blur the LCA system boundary.

Separating feedstock energy and expended energy in reporting and graphic representations should be the first, and minimum, requirement for life-cycle energy reporting. This first step would minimize misinterpretation. Feedstock energy could be further broken down to show net recoverable energy based on BAT, with a clear indication of whether recovery is a common, uncommon, or simply impractical. This step would also allow for a discussion of barriers (e.g. intolerable levels of pollution) to feedstock energy recovery.

Finally, from the perspective of sustainability, the question of whether a material contains an energy-rich fossil material may be far less important than whether the carbon tied up in the fossil energy is combusted and released as CO_2. For bitumen, other air pollution from its combustion may be an even greater concern, given current technology for burning it for energy. Either way, preventing the combustion of bitumen has environmental virtue. This means that the value of keeping these pollutants in the bitumen may overwhelm any consideration of its energy content. From this perspective, feedstock energy may be an irrelevant or at least incomplete indicator. If feedstock energy is to be reported in the impact assessment, some further interpretation of what it means for a specific material or system seems like a necessary and valuable step to understanding the life-cycle tradeoffs between materials and systems.

3 DISCUSSION OF GAPS IN LCA FOR PAVEMENT REQUIRING FURTHER WORK

Review of the literature, and the issues with LCA for asphalt pavements that are briefly highlighted in the earlier sections of this paper point out gaps in the current implementation of LCA, and indicate critical areas for further research and/or scientific debate.

The first and most apparent gap in the application of LCA to pavements appears to be the lack of clear guidelines and a consistent framework for conducting comprehensive environmental assessments of pavements. Most LCA studies in the literature focus on comparison of “asphalt” and “concrete” pavement, and attempt to draw conclusions regarding which type of pavement has the most environmental impact. However, the performance of one design or technology over another is often context-specific. The decision regarding when it is possible to complete a “fair and appropriate” comparison should be presented as context-specific, should include an assessment of uncertainty and relevance of available data, and should compare numerous impacts in order to ascertain a more comprehensive environmental footprint. Further, at this time most of these comparisons are not very useful, because the findings are case-specific, and are even confusing and, at times, detrimental to good science-based environmental policy-making because of the following gaps. Each of these gaps is illustrated in the following subsections, often using the comparison of “asphalt” and “concrete” pavement for illustration.

3.1 General Framework and System Boundary Definition

There is a gap in terms of a generally agreed upon framework for environmental LCA studies for pavement, beyond the general ISO guidelines, that consumers of that information can use to identify the scope and completeness and relevance of the study and to compare different studies. Part of the gap is in the consistent identification of which impacts are considered.

System boundary definitions must be the same between the pavement system alternatives being compared. This is very difficult when comparing very different technologies such as various types of asphalt and concrete pavement, because except for aggregate production, they use different materials which are often part of larger systems that are extremely different and difficult to compare (oil refining, cement production, fly ash recycling, steel production).

It is easier when considering alternatives that involve similar processes and materials but which differ primarily on the quantities involved. There is currently a gap in identification of appropriate system boundaries for different environmental LCA studies. As discussed previously in this paper, where processes and impacts (quantities of materials consumed and quantities of emissions) are similar, they can often be safely eliminated from the study, which should be part of the system boundary identification process.

Some system boundary definitions are more problematical, such as the energy considerations for bitumen, and many should be project-specific. For example, inclusion of the energy costs of lighting are probably appropriate for some parking lots and urban/suburban pavements, but not for rural pavements where lighting is generally not used and might be considered as pollution ("light pollution"). Pavements and roof surfaces also contribute to the urban heat island effect, which increases the need for air conditioning in hot environments and disrupts aquatic ecosystems, and has thus been discussed as a factor for pavement selection. Inclusion of heat island effects should probably depend on the local factors, and should include consideration of environmental impacts from urban heating and cooling within the same system as environmental impacts of using different pavement types/albedos as heat island reduction strategies.

3.2 Consideration of Intended Use and Regional Differences

There are gaps in data sets and more generally in previous environmental LCAs applied to pavements with regard to pavement design and construction in different regions. For example, there is no generic "asphalt pavement" that can be compared to a generic "concrete pavement" to draw conclusions that are relevant across different projects, let alone different regions or continents. Most LCA studies to date have selected one local example of an asphalt pavement and compared it to one local example of a concrete pavement, and then drawn extremely broad conclusions from an extremely limited case study. There are significant differences between projects, between regions and between continents. Defining a functional unit for pavements that can reasonably be applied over multiple regions is virtually impossible. Quantities of material and pavement material selection is very different within a region depending on local materials, climate and design traffic levels.

For example, an asphalt pavement produced for a rural road in northern California will differ significantly from an asphalt pavement built 100 kilometers away in an urban area with extremely heavy truck traffic on a different subgrade and in a different climate. The high-volume asphalt pavement in California may have a number of possible base types (including cement-treated), a design life of 40 years instead of 20 years for the rural pavement, and may be competing with three or four significantly different types of concrete pavement. As another example, asphalt pavements designed and built for the same equivalent axle loading will differ significantly if designed in California, Minnesota, Germany, China and South Africa, and it is apparent that they will have different environmental impacts.

The environmental impact of different pavement types will depend in large part on regional availability of materials, regional materials production practice, regional practice for end use (for example re-use of RAP in pavement, landfill or incineration), local mix designs and local traffic levels and climate. Unless data sets are available that are regionally applicable, the errors in LCA comparisons of different technologies will likely be much greater than the differences in calculated environmental impact between alternative pavement technologies.

3.3 Quantification and Inclusion of Rolling Resistance

There is a gap in data and in understanding regarding the interaction between pavement surfaces and roadway users. In particular, pavement micro- and macro-texture may influence vehicle fuel efficiency. The factors that influence the environmental impact of different pavement types (not just "asphalt" and "concrete") will depend not only on the materials used but on the characteristics and performance of the pavement during its use-phase. Santero and Horvath (2009) showed that rolling resistance during the use phase and its impact on vehicle energy consumption is extremely important for pavements with high volumes and high-speed traffic, while construction and materials are more important for lower volume roads because there are fewer vehicles in the use phase. Santero and Horvath's conclusions highlight the need for more detailed understanding of the pavement use-phase, both for understanding site-specific characteristics (traffic volume) and understanding interactions between the pavement and its users (rolling resistance).

There is a major gap in understanding and measurement of the impact of pavement characteristics on vehicle fuel efficiency, which is closely tied to environmental impact in the use phase. The most comprehensive datasets are from studies in the late 1970s and early 1980s that primarily looked at road geometric design and unsurfaced versus surfaced roads (Watanatada et al. 1987). The vehicles used in those studies are significantly different from the vehicles on the road today. More recent studies have not been comprehensive in terms of different vehicle fleets, operating speeds, tire alternatives and road structure and surface types. In addition, most studies to date are nearly completely empirical in nature and were not designed to validate mechanistic theories regarding the question: "what is it about this pavement that affects rolling resistance?" Most of these studies have defined pavement as "asphalt or concrete", without attempting to validate models considering tire/pavement interaction, vehicle dynamics, surface texture, etc. In addition, the parameters used to classify road surface profiles were developed for the human comfort of 1970s passenger car travelers, not characterization for vehicle rolling resistance. Better theoretical models, and focus of field experiments on their validation, are needed to be able to answer the design problem: "How do I design this road to improve fuel economy while maintaining safety?"

3.4 Environmental Impact of Secondary Materials

Secondary materials consist of waste and byproduct materials that are used in secondary applications. The use of secondary materials in pavements is quite common: the Federal Highway Administration has noted 19 different materials used in six different pavement applications (FHWA 2008). Among these applications, asphalt pavements account for the most diverse use of secondary materials, using 15 of the 19 products. However, while the use of these materials in pavements can reduce virgin material consumption and ease landfill pressures, the aggregated environmental benefits are not as routinely positive as one may initially assume.

The use of secondary materials involves tradeoffs. Intense remanufacturing processes, long transportation distances, and heightened leaching concerns are significant issues that affect the supposed environmental advantage of using waste and byproducts in pavements.

Roth and Eklund (2003) point out that the decision to use secondary materials is largely based on value choices of a particular practitioner or agency. For example, the authors assert that while the use of crushed concrete, slag, and bottom ash displaces some of the need for virgin aggregate, it also creates a potential water quality hazard. The same concept of environmental tradeoffs is echoed in many other studies. Jullien et al. (2006), Birgisdóttir et al. (2006; 2007), Carpenter et al. (2007), Huang et al. (2007) and Chiu et al. (2008) each describe situations where secondary materials provide both environmental benefits and drawbacks. Moreover, cursory economic analyses by Huang et al. (2007) and Horvath (2003) note that using secondary materials in pavements is not necessarily a financially prudent decision.

The aggregated conclusions from the existing studies indicate a need for improved understanding of how secondary materials can be used to meet specific environmental goals. Integrating life-cycle thinking into the evaluation framework will ensure that the remanufacturing, transportation, leachate and other drawbacks are considered alongside the conservation, landfilling and other benefits. Useful advancements in research would not only tally the potential benefits and drawbacks for each material, but also provide the appropriate context describing the conditions when the impacts are minimized and maximized. Such information will help decision-makers formulate insightful policies that are aligned with their individual values and objectives.

4 RECOMMENDATIONS FOR IMPROVING ASPHALT PAVEMENT LCAS

The following recommendations are made for environmental LCA for pavements based on the discussion presented in this paper.

A framework for environmental LCA applied to pavement should explicitly define appropriate system boundaries for pavement studies. Such a framework requires that discussion and consensus be reached by the pavement and LCA research communities. This discussion should be held across all sectors of the pavement community, not separately within each industrial sector. We foresee academic and government members of the community as potential leaders of consensus-based LCA framework development because of their presumably unbiased perspective on industrial sector performance.

More research is needed to develop better datasets that account for regional differences, and that are relevant to current technologies. Better datasets are need for recycling strategies and use of secondary materials, and for current technology for production of various pavement materials. Better theoretical models as well as better datasets are needed for rolling resistance. The focus of rolling resistance data should be validation of theoretical models that consider fundamental properties of pavement structures, such as surface texture, stiffness and profile; and the vehicles/tires that are operating on them.

Each of the gaps identified presents tremendous obstacles at the current time for rigorous, scientifically valid and repeatable application of LCA principles to comparison of asphalt and concrete pavements. These obstacles are also present in comparison of different asphalt-based pavement alternatives, and similarly for comparisons of different concrete pavement alternatives. However, even though the data uncertainty within a given pavement type can be significant (Kendall et al. 2009), the compounding errors when comparing pavement types have the potential to be much larger. It is therefore recommended that generic, narrowly scoped comparisons of asphalt and concrete pavements presented under the title Life-Cycle Assessment be avoided so as to not overstate the robustness of the conclusions. Instead, research should focus on evaluating alternatives to reduce environmental impact within major sectors of pavement construction, rather than between them, or perform site- and context-specific analyses that explicitly and proactively refute broad conclusions on asphalt versus concrete pavement performance.

The previous recommendation is made in part because of the blindness of many LCA studies to fiscal sustainability, as measured by life-cycle cost analysis (LCCA). For most agencies, cost is the primary criteria for selection of pavement technology. Very few agencies will routinely select a pavement with the lowest environmental impact if it is significantly more costly than the alternative. Clearly, coupling LCA and LCCA can help decision-makers compare alternatives and reach balanced conclusions. By coupling LCA and LCCA, the discourse may also be directed away from comparison of pavement types, and instead to improving material and design options within practical technology options.

In many cases, alternatives that have the lowest LCCA will also have the lowest environmental impact since pavement life-cycle costs generally increase as more virgin materials, energy, transportation, workzone congestion and construction equipment operation time are used within the life cycle.

Finally, the long-term vision for environmental LCA for pavements should aspire to inform network-level decisions regarding technology and policy, with consideration of traffic flow, evolving fleet characteristics, climate, and locally available materials and construction practices. It is recommended that this is where the major efforts of the pavement community should be devoted.

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