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A CRITICAL REVIEW OF LIFE CYCLE ASSESSMENT PRACTICE FOR INFRASTRUCTURE MATERIALS

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ABSTRACT

This paper reviews LCA studies of pavement systems to identify key sources of errors and uncertainties in LCA applied to long-lived infrastructure, and offers recommendations for reducing or quantifying uncertainties and errors. Results of this review show great variability across studies, both in their implementation and in their findings. Problems that arise in each stage of an LCA are reviewed. In the first LCA stage, goal and scope definition, findings show that many studies used narrow system boundaries that limit the interpretation of their result. For LCA parameters that are uncertain, particularly those that are expected to change over time, performing targeted scenario and sensitivity analyses on parameters that strongly influence outcomes should be used to characterize the robustness of findings. In the life cycle inventory stage of LCA, practitioners need to carefully select life cycle inventory datasets and transparently report shortcomings and uncertainty in those datasets, using statistical tools where possible to quantify uncertainty. Finally, in the third step, impact assessment, studies should consider the timing of emissions to better characterize impacts because of the long-lives of most infrastructure applications.

Keywords: Life cycle assessment, pavement, uncertainty, asphalt, concrete, greenhouse gas emissions

1 INTRODUCTION

Life cycle assessment (LCA) quantitatively assesses the sustainability of a product or system by calculating the material and energy flows and consequent environmental effects of a system from “cradle to grave.” Although the LCA framework was codified more than a decade ago, there remain unsettled questions for how to appropriately apply LCA to long-lived and complex systems such as civil infrastructure [1-3]. This paper uses examples from LCA applied to highway infrastructure to illustrate the challenges and opportunities of applying LCA to assess material sustainability. Many of the findings from this paper can be generalized to other infrastructure applications as well.

An LCA is undertaken in three primary stages: (i) goal and scope definition, (ii) life cycle inventory [LCI] assessment, and (iii) impact assessment [1]. During the goal and scope definition, LCA practitioners establish the system to be evaluated and the boundaries of the study. The LCI is the accounting stage of the study, where life cycle data for all inputs to and outputs from the system are assessed and assembled. During impact assessment the effects of the input and output flows from the LCI are translated into relevant impacts on humans and the environment. Each of these three stages introduces potential sources of variability and uncertainty that can lead to LCA outcomes that are difficult to interpret.

When practitioners apply LCA to infrastructure materials and systems, the scope and system boundaries of studies vary significantly, making comparisons across materials nearly impossible. Such differences across studies are inevitable because a material's sustainability must be evaluated in context of its application in infrastructure. The environmental impact of a material is not, on its own, an effective indicator of its performance over the life cycle of an infrastructure application [4]. Figure 1 shows how a material life cycle interacts with an infrastructure life cycle, here a pavement system.

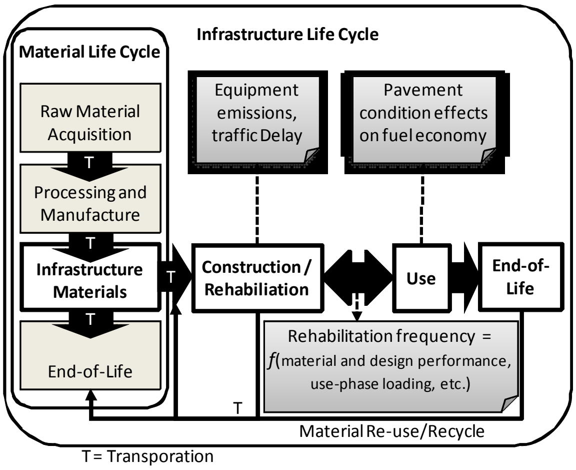

Figure 1: Interaction between a Material and Pavement Infrastructure Life Cycle

The durability of the material and the performance requirements of the infrastructure system and its users will drive the quantity of material and repair and rehabilitation frequency required by the system. This condition necessitates that the LCA of infrastructure materials be performed at the infrastructure, rather than material, scale.

This paper examines three critical factors for performing and interpreting LCAs of infrastructure materials. First, the system boundaries and purposes of highway pavement LCAs are reviewed. The review discusses the goal and system boundaries set by studies, the outcomes, and whether broad conclusions on a material's sustainability can be achieved.

The second critical factor reviewed in this paper emerges from the LCI stage of LCAs. It focuses on an impediment to our ability to reach broad, generalizable conclusions and conduct comparisons across studies: uncertainty. Uncertainty arises throughout the LCA process from numerous sources. A significant source, the one addressed primarily in this paper, is caused by LCI datasets. LCI datasets for bitumen and cement are compared and contrasted to illustrate the variability across and uncertainty within widely used LCI datasets for pavement materials.

Finally, some LCA practices that are adequate for short-lived products and systems introduce errors or distortions when applied to long-lived infrastructure systems. In particular, the practice of summing emissions over time in the LCI stage can introduce errors and uncertainty in the impact assessment stage. While this practice is problematic for most kinds of impacts, the effect of this practice on GHG emissions is discussed and potential solutions identified.

2 REVIEW OF PREVIOUS STUDIES

Numerous LCAs have been performed on highway and road infrastructure. The focus of many studies has been to compare categories of materials, namely asphalt concrete and portland cement concrete. Table 1 summarizes the findings of a number of previous pavement LCA studies. Studies that did not report GHG emissions, such as Horvath and Hendrickson (1998) and Zapata and Gabetese (2005) [5, 6], and computer-based tools, such as PaLATE, have not been included in this table [7].

Of the studies reviewed in Table 1, four of five compared the performance of asphalt and concrete. Results of two studies indicate that, as concerns GHG (represented by CO_2 or CO_2e emissions), concrete pavement performs better assuming 100% virgin asphalt is used. In two other studies asphalt pavements perform better. In addition to these two studies, the Athena Institute study found that asphalt performed better assuming a 20% recycling rate for asphalt. The discrepancy in these findings evidences the hazard of drawing broad conclusions regarding material sustainability without considering a specific infrastructure application and examining an LCA's system boundary and definition.

Discrepancies in system definition stem from a number of sources. For example, pavement system characteristics, such as the system design, material formulation, climate, construction variability, usage (e.g. traffic load), etc., may vary from site to site. A second important source of discrepancy is differences in the system boundary between studies.

The scope and system boundaries of the studies reviewed in Table 1 differ significantly from one another as well. For example, the studies by Stripple and Zhang et. al [8, 9] include at least some sources of emissions and energy from the use phase while the others do not [10-12]. Zhang et al. evaluated the interaction between pavement material and design, road roughness, and roadway users [9]. Their study's scope included all life cycle stages, including construction-related traffic congestion and some treatment of use-phase effects of pavement condition on fuel economy. They did not include other use-phase operations such as roadway lighting, which are included in Stripple (2001) [8]. However, even the two studies that did include use-phase burdens did not consider the same ones, highlighting the wide variety of scope and system boundaries in LCAs.

Zhang et al.'s findings confirmed that pavement roughness was a significant contributor to the life cycle environmental impact of an overlay design. However, the roughness--fuel economy interaction was modeled based on a linear extrapolation of two data points measured for heavy-duty trucks at low speeds [13]. Its application to passenger cars introduces significant uncertainty. Despite this uncertainty, other studies have confirmed that poor pavement condition leads to decreased fuel economy [14] and suggest pavement--vehicle interactions should be researched to better incorporate their effects in pavement infrastructure LCA.

Studies of other elements of highway infrastructure, such as bridges and overpasses, have also been conducted. Horvath and Hendrickson (1998) applied Economic Input-Output (EIO) LCA methods to compare steel and steel-reinforced concrete bridge girders and to evaluate the materials production, girder maintenance, and end-of-life stages [14]. Keoleian et al. (2005) compared two bridge deck designs using LCA and accounted for materials production, construction and maintenance activities, and impacts of construction activities on vehicle traffic. They did not, however, fully account for end-of-life activities [15]. Both of these studies focused on retrofits of an existing structure, so supporting infrastructure was not examined and no fuel economy effects were considered.

Table 1: Review of LCA Applied to Pavement Materials and Systems

Ref. No., Author(s)	Year	Scope	Key Findings for GHG emissions	Treatment of Uncertainty / Sensitivity
[8] Stripple	2001	Pavement construction and materials comparison of asphalt and concrete over a 40-year time horizon. Vehicle traffic is not considered, except in a sensitivity analysis	Lighting and traffic control during operation are key sources of energy consumption and consequent GHG emissions. Asphalt pavements perform better for CO_2 emissions, and are dominated by construction emissions	Some sensitivity to timing of construction (e.g. best/worst scenarios). Also tested the contribution of traffic (5000 AADT) to life cycle emissions and energy
[12] Park et al.	2003	Asphalt pavement system that considers earthwork along with other construction and rehabilitation activities, 20-year time horizon	This is a baseline study for Korean roads. No significant conclusions are drawn, and it appears that the study assumes an asphalt pavement system only - though this is not clear	None
[10] Athena Institute	2006	Comparison of portland cement concrete and asphalt concrete roadway designs, subbase included, 50-year time horizon	For 100% virgin asphalt systems, portland cement concrete had lower CO_2e* emissions. For 20% recycled asphalt content, asphalt concrete performed slightly better	Scenario analysis for different roadway types and capacities, also 0% and 20% recycled asphalt content in asphalt mixes
[9] Zhang et al.	2008	Overlay on existing pavement surface. Contruction, materials, and traffic over a 40-year service life for asphalt, concrete and ECC	ECC best, then concrete, then asphalt for CO_2e emissions, dominated by materials, roughness effects on fuel economy, and construction-related congestion. Other pollutants are variable, though ECC tends to perform best	Sensitivity to traffic growth rate
[11] Chiu et al.	2008	Asphalt pavement and concrete pavement (40-year life cycle), materials, construction	Findings show asphalt pavement performs better on CO_2 emissions as well as all other energy and emissions categories	Evaluated low-emission and normal vehicles

* CO_2e refers to CO_2-equivalent emissions, which are calculated by multiplying non-CO_2 GHGs by their global warming potentials, and summing all CO_2 and CO_2e emissions over the life cycle.

Kendall et al. (2008) also evaluated the performance of alternative mix designs for engineered cementitious composite (ECC) materials used as bridge deck link slabs and found that initial material energy intensity did not correlate with life cycle energy [4]. In addition, some materials did not benefit from improved material performance because they outlived the life cycle of the structure in which they were used. While Kendall et al. (2008) only reported results for energy consumption its findings confirm the importance of evaluating material sustainability in the context of its use in specific infrastructure applications.

3 UNCERTAINTIES IN INFRASTRUCTURE LCA

Uncertainty and variability are factors that complicate the interpretation of LCA outcomes. Uncertainty and variability emerge from different origins. Uncertainties arise from lack of knowledge, while variability is inherent in the nature of data itself. Uncertainty may be the result of data unavailability, data inaccuracy, or data ambiguity while variability relates to non-homogeneity and unpredictability in the real world.

Despite the obstacle presented by uncertainty in the interpretation of LCA outcomes, few LCAs applied to any system report uncertainty in their results. Ross et al. (2002) reviewed 30 LCA studies that followed the standard LCA methodology between 1997 and 2002 and found that less than half (47%, 14 out of 30) of the studies reported uncertainty [15]. More surprisingly, only three studies performed a quantitative or a qualitative analysis on uncertainties. Table 1 shows that while some pavement LCAs examine sensitivity to certain assumptions; more sophisticated methods for addressing uncertainty have not been adopted.

Huijbregts (1998) presented a list of possible uncertainties that arise in LCAs: parameter uncertainty, model uncertainty, uncertainty due to choices, spatial variability, temporal variability, and variability between sources and objects [16]. These uncertainties emerge at different stages of an LCA, and increase with the complexity and time horizon of study.

Sources of uncertainty in LCAs such as uncertainty due to life cycle inventory datasets exist regardless of the time horizon or complexity of the study. Infrastructure LCAs must predict future events and conditions. This adds uncertainty to the LCA (Figure 2). Some LCAs address this by assuming that current conditions (e.g. material production technologies, climate, resource availability, etc.) remain static over time. Others take a temporally dynamic approach that varies one or more parameters expected to change over time (e.g. traffic flow, pavement condition, vehicle technology, etc.).

Figure 2 shows examples of sources of uncertainty in static and temporally dynamic LCAs. This figure does not imply that a static LCA of a long-lived infrastructure system has less uncertainty than a temporally dynamic one. After all, many parameters are likely to change over time and a static model of a long-lived system fails to include these likely changes.

As shown in Table 1, many pavement LCAs attempt to compare life cycle material performance for asphalt and concrete materials. Many of the studies reviewed found that there were small benefits to one material over another, indicating that the preference for one material or design over another would be easily changed. None of the studies, however, examined the uncertainty of their underlying life cycle inventory datasets.

This paper will address only one of the myriad sources of uncertainty in LCA of infrastructure materials: uncertainty in LCI datasets.

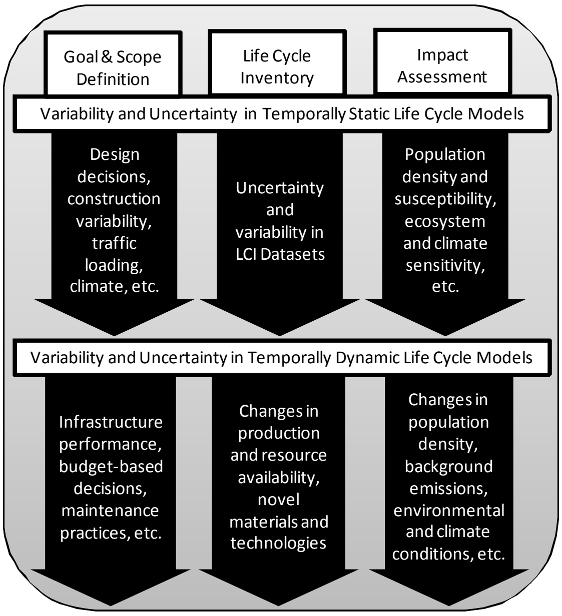

Figure 2: Sources of Uncertainty in LCA Applied to Pavement Infrastructure

3.1 Uncertainty in LCI Datasets

Differences between LCI datasets can arise from either variability or uncertainty. Variability among datasets may result from real regional or technological differences and the level of aggregation across a region. This source of variability can be managed by better documenting data sources and selecting technologically and geographically-appropriate datasets. However, because LCI datasets are scarce, LCA practitioners often rely on datasets that do not reflect the appropriate region or technology.

Uncertainty in LCI datasets is more difficult to address because many datasets do not report any kind of uncertainty or statistical information for the point estimates reported in an LCI. In the following comparison of LCI datasets, uncertainty and variability are not distinguished, because it is impossible to do so. Instead, this section discusses the differences observed across datasets with both variability and uncertainty in mind.

Bitumen is an important component of many pavement systems as it is the binder for asphalt concrete. The binder, rather than the composite asphalt concrete material was chosen to eliminate additional variability caused by alternative asphalt concrete mix designs. Figure 3 shows CO_2e emissions for three different life cycle inventory datasets for bitumen.

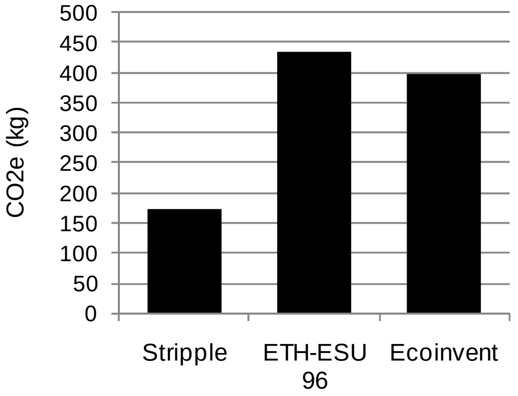

Figure 3: CO_2e Emissions per ton of Bitumen for Various Life Cycle Inventory Datasets [8, 17, 18]

Figure 3 shows more than a 150% difference between the Stripple (2001) dataset and the ETH-ESU 96 dataset [8, 18]. There are many likely sources of variability between the two datasets.. Geographic differences, for example, can contribute to variability in the type of crude oil used in bitumen production, the refinery design, and transportation burdens for raw materials.

Bitumen production occurs at refineries where many petroleum products are produced. The process for assigning production burdens to each product, referred to as co-product allocation, can introduce yet another source of variation between LCI datasets. The methods for co-product allocation used to produce the ETH-ESU 96 and Ecoinvent datasets is not entirely clear; however, Stripple (2001) used a weight-based allocation method for bitumen, and assumed that heavy crude oil from Venezuela was used at the refinery. These assumptions and allocation methods influence the outcome of an LCI, and may, in part, explain the differences observed between these datasets.

As exemplified by the assumption of crude oil sources, resource abundance and availability over time will also influence the LCIs for asphalt production. These factors could be important considerations when designing long-lived infrastructure applications or deciding on rehabilitation schedules.

Cement is the primary binder in concrete. Cement, LCIs evaluated for the same reasons as described for evaluating bitumen LCIs. Figure 4 shows six LCIs for cement production. As observed for bitumen, variability across LCIs for cement is considerable.

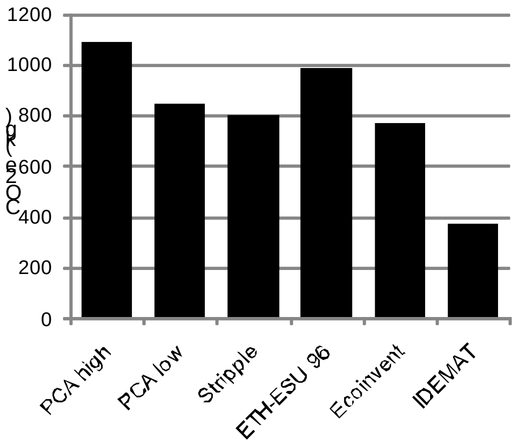

Figure 4: CO_2e Emissions per ton of Cement for Various Life Cycle Inventory Datasets [8, 19-22]

The PCA high and PCA low categories in Figure 4 refer to different assumptions in production technology at U.S. cement plants [22]. The high refers to the wet production process, which is the most CO_2-intensive. The low refers to preheater production technology, which is the least CO_2-intensive. These two LCIs show that simply the type of production technology used in the same region can change CO_2e emissions estimates by almost 30%.

The IDEMAT dataset shows CO_2e emissions at less than half of all the other datasets [21]. This may simply be an error in the dataset, or it may be because CO_2 emitted by the limestone during pyroprocessing was left out of the dataset. Even if this dataset is considered an outlier, there is still considerable variability between LCI datasets.

As with the bitumen LCI datasets, differences could, in part, be explained by differences in the geographic location and subsequent variation in fuel sources, raw materials, electricity mix, and production technologies used at facility.

The datasets in Figure 4 illustrate the importance of obtaining LCI datasets that reflect the appropriate technology, geographic region of study, and time. The development of future life cycle inventory datasets should include statistical measures of dataset certainty to facilitate the use of more sophisticated tools to quantify total uncertainty in LCAs [13].[1]

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[1] The Simapro software tool [13] has included some measures of uncertainty in datasets from the Ecoinvent database and provided Monte-Carlo simulation options in their software tool.

4 CHALLENGES FOR IMPACT ASSESSMENT OF LONG-LIVED INFRASTRUCTURE MATERIALS

The impact assessment stage of LCA attempts to assess as accurately as possible the actual effects of the inputs and outputs from the system evaluated. Overwhelmingly, the results from LCIs and impact assessments are reported as the total sum of emissions or impacts from emissions that occur over the life cycle of the system evaluated [23]. Consider the tendency to report gases that cause global warming as the sum of their CO_2e. For short-lived products this practice is acceptable. After all, if emissions occur over a short time horizon in the near term, impacts based on the sum of emissions may be reasonably assessed.

However, for long-lived systems this practice may distort the actual effect of emissions. For many pollutants, for example, the background concentration and the susceptibility and density of the population exposed to the pollutant influence the impact assessment step in LCA. These characteristics are likely to change over time, as population and human activities that produce pollutants increase.

For emissions that cause global warming, the practice of summing emissions over time introduces a slightly different problem, but still misrepresents the impact of emissions that occur sooner rather than later.

A GHG causes global warming by trapping radiation in the atmosphere. The cumulative effect of a GHG increases with the time it remains in the atmosphere. All else equal, an emission released sooner has more global warming effect than one released later when evaluated at a future point in time.

GWPs developed by the Intergovernmental Panel on Climate Change (IPCC) are used in LCA to convert non-CO_2 gases to their CO_2e [24]. The IPCC uses cumulative radiative forcing (CRF) to assess the relative impact in the calculation of GWPs. GWPs are based on the relative CRF between some GHG and CO_2, the most common GHG. CRF is calculated by integrating a gas's radiative forcing over some specified time horizon, for GWP calculations usually 100 years.

Because the CRF is calculated by integrating radiative forcing over a time horizon, the CRF of a gas released in 2009 and evaluated at 2029, will be larger than the same emissions released in 2019 and evaluated in 2029. Yet in LCA, we ignore this difference by summing gases over time without reference to their date of emission. For a more in-depth discussion of this problem see O'Hare et al. (2009) or Kendall et al. (2009) [25, 26].

To demonstrate the importance of emissions timing in infrastructure LCA, consider the results reported in the Athena Institute study reviewed in Table 1 that compared a 100% virgin asphalt pavement system and a concrete pavement system [10].[2]

The study found that the concrete pavement system requires an upfront emission of 554 t of CO_2e for the initial construction event, but does not require reconstruction or significant rehabilitation over the next 50 years. The asphalt pavement system requires a smaller initial GHG emission of 335 t CO_2e, with an additional 200 t CO_2e emitted at year 17 due to a rehabilitation event. The study did not consider the effect of the pavement system on vehicle traffic and performance, nor did it consider any other processes during roadway operation.

If typical LCA methodology is used, the results show a total CO_2e of 554 t for the concrete pavement, and 555 t for the asphalt pavement, resulting in a slightly worse performance for the asphalt system. Whether we simply compare t CO_2e or the CRF of the emissions treating them as if they are released at the same time, the performance of the two systems from a global warming perspective are essentially identical, with the asphalt system showing slightly larger global warming effects. Figure 5 shows the CRF for both systems assuming that the emissions occur at the same time at year zero.[3] The concrete system is shown by the dashed black line and the asphalt system by the white line. From the perspective of CRF, the global warming effects of each system are essentially indistinguishable.

If we consider the actual timing of emissions for both systems, however, the global warming effects of each system are quite distinct. Figure 5 illustrates that when the timing of asphalt system emissions is accounted for, shown with the solid black line, the asphalt pavement system clearly has less global warming effect than the concrete system.

At 50 years in the future, the planning time horizon used in the source study, the concrete system has a 10% higher global warming effect as measured by CRF, reversing the conclusions we would draw from simply summing the CO_2e emissions. If we examine CRF at a 100 year time horizon, the time horizon typically used for GWP calculations, the concrete pavement system still has a 5% great CRF than the asphalt system. Simply by accounting for GHG emissions timing, the preference for one pavement system over another is reversed.

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[2] The numbers used in this calculation are from the "CBR3" system.

[3] The calculations here use the CRF equation from the IPCC's Fourth Assessment Report, and treats all CO_2e emissions as CO_2 [24]. This is a simplification, but given that most emissions from pavement systems are CO_2, it should introduce little error.

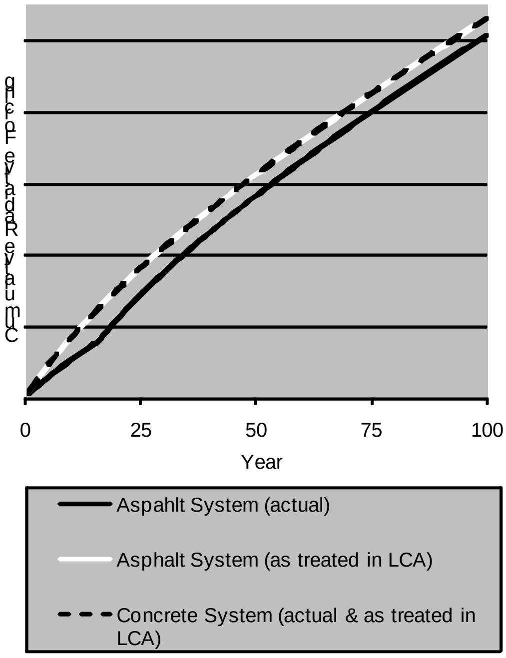

Figure 5: CRF for GHG emissions from the 100% Virgin Asphalt and Concrete Pavement Systems in [10]

The Athena Institute study did not account for use-phase GHG emissions, resulting in an LCA with a very limited system boundary. Thus, while this exercise shows that accounting for emissions timing can reverse or at least change the outcomes of a study, the limited system boundary of this specific study means that we should not draw hasty conclusions about the global warming performance of either system.

Inclusion of the use and operation phase could significantly alter the results. For example, Stripple (2001) found that the operational phase for concrete required less lighting due to higher surface reflectivity. Kendall et al. (2008), Zhang et al. (2008), and Keoleian et al. (2005), found that reducing future repair activities significantly reduced construction-related traffic congestion, particularly if future increases in traffic flow rate were considered [4, 9, 27]. Finally Zhang et al. (2008) considered pavement condition effects on vehicle fuel economy, and found this also to have considerable influence on life cycle GHG emissions [9]. None of these use-phase GHG emissions sources were included in the Athena Institute LCA [10].

5 CONCLUSIONS AND RECOMMENDATIONS

The results shown in sections 3 and 4 highlight just three of the many challenges faced by LCAs applied to infrastructure materials and systems that compromise our ability to interpret results and definitively select one infrastructure material or design over another. However, the recommendations provided in each section of the results suggest some initial steps for designing and implementing improved LCAs for infrastructure materials.

During the first stage of LCA, the goal and scope definition, the use and operation phase is often left out of the study. The studies that did include elements of the use and operation phase found them to be influential in the outcome. Future studies should not omit this phase. In addition, while there is limited data available, including the effects of pavement condition on vehicles and trucks seems to be influential, though the relationship has not been sufficiently explored.

In the LCI stage of LCA, there is considerable variability and uncertainty in datasets. To minimize this, LCA practitioners must be careful to use geographically and temporally appropriate datasets. When appropriate datasets are not available, transparent reporting and discussion of dataset shortcomings should be included.

Current LCA practices such as summing emissions over time prior to impact assessment are particularly problematic. For global warming effects in particular, this practice distorts the global warming effects of one system over another due to the importance of emissions timing. For this reason, metrics such as CRF and other measures of GHG effects on global warming can be reported in order to better compare alternative long-lived systems.

Finally, infrastructure material sustainability must be considered in the context of an infrastructure application. Thus, LCAs do not provide broad conclusions about a material’s sustainability, but instead may provide conclusions on the sustainability of one material over another in the context of a specific infrastructure application.

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