A CRITICAL REVIEW OF LIFE CYCLE ASSESSMENT (LCA) PRACTICE FOR INFRASTRUCTURE MATERIALS

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Study Approach

- We’ll examine pavement materials as a case study of LCA applied to infrastructure materials
- Highlight many of the challenges and shortcomings we face when conducting LCAs
- Make recommendations for improving transparency and reducing variability across studies
Study Approach

- We use the primary LCA steps as outlined by ISO/SETAC/EPA for process-based LCAs as the framework for evaluation.
- Examine key problems or challenges at each stage.
- Not an exhaustive review of the literature or challenges, but intended to initiate discussion.
- Infrastructure materials must be considered in the context of their application.
Three Key Elements of Life Cycle Assessment

1. **Goal Definition and Scope**
   - Establish the system to be evaluated (design, location, etc.) and the boundaries of the study.

2. **Life Cycle Inventory Assessment**
   - Inputs to and outputs from the system are assessed and assembled.
   - LCI are translated into relevant impacts on humans and the environment.

3. **Impact Assessment**

   At each stage sources of uncertainty and variability are introduced.

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Figure based on ISO 14001
Variability and Uncertainty in Temporally Static Life Cycle Models

- Design decisions, construction variability, traffic loading, climate, etc.
- Uncertainty and variability in LCI Datasets
- Population density and susceptibility, ecosystem and climate sensitivity, etc.

Variability and Uncertainty in Temporally Dynamic Life Cycle Models

- Infrastructure performance, budget-based decisions, maintenance practices, etc.
- Changes in production and resource availability, novel materials and technologies
- Changes in population density, background emissions, environmental and climate conditions, etc.
Three Key Elements of Life Cycle Assessment

- Goal Definition and Scope
- Life Cycle Inventory Assessment
- Impact Assessment

Figure based on ISO 14001
Goal and Scope Definition

- **Purpose of study**
  - Comparative vs. Baseline

- **System Boundary**
  - What life cycle stages are considered?
  - What processes from each life cycle stage are included in the study?
## Comparison of Scope for Five Pavement LCA Studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Scope</th>
<th>Key Findings for GHG emissions</th>
<th>Treatment of Uncertainty / Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stripple</td>
<td>2001</td>
<td>Pavement construction, and materials comparison of asphalt and concrete over 40-years. Traffic not considered except in a sensitivity analysis</td>
<td>Asphalt better for CO₂ emissions, and results are dominated by construction emissions. Lighting and traffic control are important.</td>
<td>Some sensitivity to timing of construction (e.g. best/worst scenarios). Also tested traffic flow.</td>
</tr>
<tr>
<td>Park et al</td>
<td>2003</td>
<td>Asphalt pavement system that considers earthwork along with other construction and rehabilitation activities, 20-year time horizon</td>
<td>This is a baseline study for Korean roads. Assumes an asphalt pavement system only - though this is not clear</td>
<td>None</td>
</tr>
<tr>
<td>Athena Institute</td>
<td>2006</td>
<td>Comparison of portland cement concrete and asphalt concrete roadway designs, subbase included, 50-year time horizon</td>
<td>For 100% virgin asphalt systems, concrete had lower CO₂e* emissions. For 20% recycled asphalt content, asphalt slightly better</td>
<td>Scenario analysis for different roadway types and capacities, also 0% and 20% recycled asphalt content in asphalt mixes</td>
</tr>
<tr>
<td>Zhang et al</td>
<td>2007</td>
<td>Overlay: Construction, materials, and traffic over a 40-year service life for asphalt, concrete and ECC</td>
<td>ECC best, then concrete, then asphalt for CO₂e emissions</td>
<td>Sensitivity to traffic growth rate</td>
</tr>
<tr>
<td>Chiu et al</td>
<td>2008</td>
<td>Asphalt pavement and concrete pavement (40-year life cycle), materials, construction</td>
<td>Asphalt pavement performs better on CO₂ emissions as well as all other energy and emissions categories</td>
<td>Evaluated low-emission and normal vehicles</td>
</tr>
</tbody>
</table>

Only two studies consider the use-phase. But they don’t consider the same use-phase process!
The Pavement Use-Phase

- The two studies that considered use-phase processes in their LCA found they were influential.

- Important uncertainties not fully addressed in current LCAs:
  - Pavement-vehicle interactions
    - Though studies have begun to consider this (e.g. Zhang et. al) our understanding of what the fuel economy effect of pavement surface characteristics is not sophisticated.
Three Key Elements of Life Cycle Assessment

- Goal Definition and Scope
- Life Cycle Inventory Assessment
- Impact Assessment

Interpretation

Figure based on ISO 14001
Uncertainty in LCI Datasets

- LCA studies rely on life cycle inventory datasets. These datasets are compiled by firms and public entities based on real data from specific facilities, average data from many facilities, or engineering calculations.
- The time horizon over which data are collected, the year the data is collected, and of course the location of collection may all influence the LCI dataset.
To reduce the differences in datasets due to variations in mix design, we examine datasets for the primary binders used in asphalt (bitumen) and concrete (cement).

These datasets are derived from reports and databases accessed through a widely-used LCA software tool (Simapro).
GHG emissions per kg bitumen

<table>
<thead>
<tr>
<th></th>
<th>Stripple</th>
<th>ETH-ESU 96</th>
<th>Ecoinvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2e (kg)</td>
<td>150</td>
<td>450</td>
<td>390</td>
</tr>
</tbody>
</table>
GHG emissions per kg cement

- PCA high
- PCA low
- Stripple
- ETH-ESU 96
- Ecoinvent
- IDEMAT

CO2e (g)
Three Key Elements of Life Cycle Assessment

- Goal Definition and Scope
- Life Cycle Inventory Assessment
- Impact Assessment

Interpretation

Figure based on ISO 14001
Uncertainty and Variability in Impact Assessment

- Lots of uncertainty and variability
  - Uncertainty
    - How do pollutants effect ecosystems, people, climate, etc.
  - Variability
    - The effect of a pollutant varies due to many factors such as background emissions, population density, ecosystem sensitivity, and timing

- Here we examine greenhouse gas (GHG) emissions timing only
  - Timing and/or location are important for all pollutants however
What does CO$_2$e mean?

- Global warming potentials convert non-CO$_2$ GHGs to CO$_2$ equivalent (CO$_2$e)

Impact Chain for Global Warming

Increase in radiative forcing (RF)

A build up of heat due to RF over some time

Atmospheric warming

Eventual Temperature Change

Climate Change

This stage is called cumulative radiative forcing (CRF)

Global Warming Potentials
How GWPs are Calculated

\[ GWP_{i,TH} = \frac{\int_0^{TH} RF_i \, dt}{\int_0^{TH} RF_{CO_2} \, dt} \]

- TH = Time Horizon
- 100 years is a common time horizon
- IPCC also reports 20, and 50 year time horizons

Note: RF is dynamic for all GHGs of concern, since concentration is constantly changing!
The Impact Chain: GHGs

- Most LCAs (and most new legislation) rely on the IPCC estimates for global warming potentials (GWPs) to convert non-CO$_2$ GHGs to CO$_2$e.
- CO$_2$ GWP$_{100}$ = 1
- CH$_4$ GWP$_{100}$ = 25
- N$_2$O GWP$_{100}$ = 296
- We typically just sum up GHGs over the time horizon of study.
What does this mean for how we model CO2 in the Atmosphere?

Imagine an emission that occurs in year one with a value of 1. Then imagine if this value is spread out over 20 years (e.g. 1/20 emitted each year).
How does this change modeled CRF?
CRF Based on Athena Institute Study

- Compared asphalt and concrete over 40-year time horizon
- Assumed asphalt would need to be replaced at year 20, but concrete would not
- Results showed no demonstrable differences between global warming effects (represented as CO₂ equivalent) between the two designs
CRF Based on the Athena Institute Study
(all emissions at year zero)

If we ignore emissions timing, asphalt and concrete look the same.
CRF Based on the Athena Institute Study (Actually emissions timing included)

- Asphalt System (actual)
- Asphalt System (as treated in LCA)
- Concrete System (actual & as treated in LCA)

Asphalt requires replacement at year 20.
Recommendations

- **Goal and Scope**
  - LCA’s need to align system boundaries if we are to reasonably compare across studies
  - For pavement LCAs we really need to include the use-phase and better understand use-phase processes

- **Life Cycle Inventory**
  - Uncertainty in LCI datasets should be explicitly included in studies

- **Impact Assessment**
  - GHG emissions timing must be considered when we examine long-lived systems using LCA
    - This includes emissions or “sequestration” (e.g. absorption of CO₂)
  - This increases the reporting burden for LCAs but facilitates transparency and re-interpretation of results
Questions?

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