Life Cycle Assessment of Pavements

Sensitivity Analysis

Alex Loijos, alex@mit.edu
Mehdi Akbarian, akbarian@mit.edu
Sahil Sahni, sahil@mit.edu
John Ochsendorf, jao@mit.edu
Outline:

Study Goals
Literature Review
Methodology
Phases and Components
Results
Why and How
Problem Statement and Goals

Concrete:
- Most consumed material on earth after water
- U.S. Cement production is the second most GHG intensive industry after steel
- Transportation accounts for 29% of total U.S. GHG emissions. (EPA 2006)
- Over 4 million miles of pavement in the US alone

Equal to driving back and forth to the moon 8 times

Problem statement and goals:
How do GHG emissions in the pavement life cycle vary under different engineering and policy scenarios and where are the largest opportunities to reduce emissions?
Literature Review

- Ranges of impact for pavement LCA

  “Because the impact is context-sensitive, there is no single component that can be considered the least or most influential under all circumstances.”

  While broader than most studies, does not include:
  - Differentiation between asphalt and concrete
  - Influence of maintenance
  - Recycling/End of life
Methodology

Life Cycle Assessment framework:
- System boundary definition
- Inventory
  - Inputs – energy and materials needs
  - Outputs – waste and emissions
- Impact Assessment
  - Global Warming Potential in CO$_2$e
  - Interpretation of the results

Functional Unit:
- 1 m$^2$ of paved surface with 50 year lifetime

Software: GaBi 4 by PE International + US Construction database

Life Cycle of Pavements

Recycling
Resource Extraction
Processing
Placement
Use Phase
Maintenance

LCA Boundaries
No capital goods
Dynamic Model

Identify pavement parameters and life cycle phases.
Phases and Components
Materials Production
Binder Extraction and Manufacturing

Raw Material Extraction and Initial Transformation
Manufacturing
Placement
Use and Maintenance
Removal, Recycling, and Disposal

Relevant Parameters
- Overlay depth/density
- Overlay composition
- Facility technology
- Fly ash/other substitution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bitumen</th>
<th>Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg CO2e per kg</td>
<td>0.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>

1.6 kg CO2e per kg
1.8 kg CO2e per kg
Other Materials and Mix Manufacture

Aggregate:

Steel Production:
- ~20 GJ/ton
- GHG emissions: 1.45 kg CO2e per kg

Concrete Mixing:
- Not energy intensive

Hot Mix:
- Drying aggregate is the most GHG intensive activity of production life cycle

1- NCSA (1997); Stammer and Stodolsky (1995); NCSA (1997)
Transportation Phase
## Cement Transport Average Distance by Mode

<table>
<thead>
<tr>
<th>Mode</th>
<th>Min Dist</th>
<th>Avg Dist</th>
<th>Max Dist</th>
<th>% Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trucked</td>
<td>83 km</td>
<td>167 km</td>
<td>322 km</td>
<td>70%</td>
</tr>
<tr>
<td>Barged</td>
<td>0 km</td>
<td>1400 km</td>
<td>5600 km</td>
<td>30%</td>
</tr>
</tbody>
</table>

2 Imports – Extreme: China → New Jersey
## Aggregate Transport Average Dist. by Mode

<table>
<thead>
<tr>
<th>Mode</th>
<th>Distance</th>
<th>St. Dev.</th>
<th>% Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td>50 km</td>
<td>12 km</td>
<td>26%</td>
</tr>
<tr>
<td>Rail</td>
<td>507 km</td>
<td>25 km</td>
<td>61%</td>
</tr>
<tr>
<td>Barge</td>
<td>170 km</td>
<td>45 km</td>
<td>13%</td>
</tr>
</tbody>
</table>

### Extreme Practice

Crushed aggregate arriving from British Columbia to San Francisco

From US Commodity Flow Survey 2007

From jericoproducts.com
Barging Efficiency

ONE BARGE = 4000 tons

40 100-TON RAIL HOPPER CARS
160 25-TON TRAILER TRUCKS

CO2e per 100 kg-km:
- Barge 1.3 g
- Rail 3.4 g
- Truck 6.0 g
Use Phase
Use Phase Assumptions

Account only for *increase or decrease* in emissions due to the pavement’s existence

- Road roughness
- Fuel consumption

The same attribution goes for albedo and roadway lighting
Rolling Resistance

The largest known life cycle GHG contribution

Two effects: Pavement structure and pavement roughness

Figure 3. Illustration of asphalt (left) and concrete pavement rolling resistance


Parameters
- Pavement type
- Traffic volume
- Traffic composition
- Base fuel efficiency
- Temperature
  etc.
Albedo Effect

Urban heat island effect

Q: What’s the effect in cold climates?

Radiative forcing

Trumps heat island effect by ~10 times

- Varies according to:
  - Pavement type – asphalt or concrete
  - Pavement age
  - Specialty whitener chemicals

Carbonation

- Between 1.4% and 15% of CO$_2$ is reabsorbed, depending on pavement material properties

Maintenance
Pavement Service Life

Service life is highly variable, and strongly effects energy and resource needs throughout 50 year life

<table>
<thead>
<tr>
<th></th>
<th>Concrete</th>
<th>Asphalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme Low</td>
<td>17.5</td>
<td>7</td>
</tr>
<tr>
<td>Normal Low¹</td>
<td>23</td>
<td>13</td>
</tr>
<tr>
<td>Normal High²</td>
<td>28.5</td>
<td>16</td>
</tr>
<tr>
<td>Extreme High</td>
<td>50</td>
<td>20</td>
</tr>
</tbody>
</table>

1- Croney 1997, Gharabeh 2003, Bentz 2001
Results
Normal Sensitivity Range

![Graph showing the global warming potential of concrete in kg CO₂ per m². The graph is divided into Production Life Cycle and Use Phase, with values for materials extraction and production, construction, transportation, and total production and production + use phase.]
Use Phase Range

[Bar chart showing global warming potential (kg CO₂e per m²) for various factors in use phase.]

- Radiant
- Carbonation
- Lane closure
- Lighting
- Rolling resistance
- Total Use Phase
Sensitivity to Maintenance

Production Life Cycle

<table>
<thead>
<tr>
<th>Phase</th>
<th>Global Warming Potential (kg CO₂e per m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Extraction</td>
<td>55</td>
</tr>
<tr>
<td>Construction</td>
<td>97</td>
</tr>
<tr>
<td>Transportation</td>
<td>89</td>
</tr>
<tr>
<td>Use Phase</td>
<td>165</td>
</tr>
<tr>
<td>Transportation</td>
<td>104</td>
</tr>
<tr>
<td>Use Phase</td>
<td>69</td>
</tr>
<tr>
<td>Total Production</td>
<td>10733</td>
</tr>
<tr>
<td>Total Production + Use</td>
<td>27683</td>
</tr>
<tr>
<td>Total Production</td>
<td>18676</td>
</tr>
<tr>
<td>Total Production + Use</td>
<td>28053</td>
</tr>
</tbody>
</table>

Legend:
- Asphalt
- Concrete
- Extreme Range
Conclusions

- Results of LCA are highly dependent on the initial assumptions.
- There are many opportunities across the life cycle for improvement.
- The use phase dominates under any initial conditions.
- Maintenance 2nd largest component and a trade-off with rolling resistance.
Future Work

- Improve Data Quality
- Detailed Scenario Analysis
  - 1) Decrease surface roughness by increasing preventive and rehabilitative maintenance
  - 2) Leverage albedo effect and include whitening chemicals in LCI
  - 3) Engineered Cementitious Composite (ECC), etc.
  - 4) Model fly ash, rice husk ash, etc.
- Life cycle costing
- Create tool for engineers to estimate their pavement’s carbon footprint
Thank You!

Questions?