Asphalt Pavement Life Cycle Assessment: Review and Future Outlook

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Development Strategy of Road Engineering
Harbin Institute of Technology
Harbin, China
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Outline

• Review of sustainability goals
• Changes in transportation that will affect pavement
• Tools for measuring sustainability
• Implementation
• Prioritization
• Conclusions
Sustainability: Master equation for environmental impacts

Environmental impact = Population * GDP / Person * Impact GDP

Increase in wealth and economic activity

Ehrlich and Holdren (1971) Impact of population growth. e.g. via LCA
*Science 171, 1211-1217
Slide adapted from R. Rosenbaum, Pavement LCA 2014 keynote address

New technology, organization and implementation
Climate Change: California targets for GHG

- State law remains; federal withdrawal from Paris Agreement
- 2020 targets: will be met, primarily in energy sector
- 2030, 2050 targets: much harder, requires many more strategies

Air Resources Board Climate Scoping Plan
Climate Change: can California state goals be met and keep a strong economy?

- Population growth:
  - 1990: 30 million
  - 2017: 39 million
  - 2055: 50 million
How could changes in pavements reduce California GHG emissions?

• Out of 459 MMT CO2e in 2013
  – On road vehicles 155 MMT
    • Reduce rolling resistance to optimum = - 1.5 MMT
    • Reduce hauling of stone 10% = - 0.6 MMT
  – Refineries 29 MMT
    • Reduce asphalt use 50% = - 0.7 MMT
  – Cement plants 7 MMT
    • Reduce cement use 50% = - 0.2 MMT
• Total pavement reductions = - 2.9 MMT
  = 0.6% of state total GHG

http://www.arb.ca.gov/cc/inventory/data/data.htm

These are important contributions to GHG reduction

Equally important is what changes in other parts of economy will do to pavement
Pavement Materials Resource Depletion and Replacement

• Aggregate:
  – Local future shortages and quality issues
  – Large quantities of aggregate moved on the roads, = lots of fuel use, high levels of damage on roads

• Asphalt:
  – US: supply and demand balanced, because large amounts of asphalt are coked for liquid fuels
  – If oil demand for transportation fuel diminishes, there is a nearly infinite future supply of asphalt
  – Will there be a business model to refine oil for asphalt?
Air Pollution Toxicity is also very important

- Transportation related factor of most importance is air pollution, especially diesel trucks
  - Requiring changes in vehicle energy sources, especially trucks
  - Less oil refining

http://graphics.latimes.com/responsivemap-pollution-burdens/

Truck traffic axle weights increasing?

- State-wide average axle loads (115 WIM stations) virtually unchanged in 10 years
- Gross vehicle weights slightly reduced
Freight growth: more trucks

- 62% increase in truck counts vs 14% growth in population
- Short-haul: 69% increase
- Long-haul: 59% increase

UCPRC/Caltrans WIM data
Electric vehicles and weight

- Currently about 30% heavier for about 30% of the range
- Trucks use same technologies as cars, more range = add more batteries
- Fuel cells questionable

DeMorro, 2015,
https://cleantechnica.com/2015/03/17/lighter-batteries-may-prove-tipping-point-electric-vehicles/
Long and short haul trucks available now
WAZE. OUTSMARTING TRAFFIC, TOGETHER.

What is wrong with this image if trucks use Waze and you are a local government?
Autonomous Vehicle Technology

• Fully automated truck platooning expected to deploy starting 2020 and broad implementation by 2030
  – 3 to 13% fuel savings
• Asphalt surfaced pavement
  – Channelized traffic if wander is not programmed into guidance, = faster rutting and fatigue
  – Truck platooning will reduce thixotropic recovery times at high speeds, larger strains
• Automated Vehicles Symposium 2017 and 2018
  – No discussion of effects on pavement
What kind of pavement will we need in the future?

Millennials driving the trend; may not just be recession

Less interested in cars; use of technology to connect instead of travel; more interested in walkable, bikeable cities; fewer or more vehicles

Summary of Sustainability Goals

• Respond to changes in vehicle technology
• Save the planet from excessive global warming
  – Reduce greenhouse gas emissions from pavement and interactions of pavement with other systems
• Reduce local emissions harming people
  – Air pollution, water pollution, etc
• Do not use finite resources too quickly
• Maintain economic competitiveness
• Improve pavement effects on human quality of life
• Achieve equity to all people in access to opportunities provided by pavement
  – Access to education, health care, jobs, recreation
Tools for Measuring Sustainability

• Life Cycle Cost Analysis (LCCA)
  – Economic

• Life Cycle Assessment (LCA)
  – Range of environmental impacts, quantitative

• Social Life Cycle Assessment (S-LCA)
  – Indicators for social outcomes and equity

Reasons to Measure

  Decision support
  Establish baselines for process improvement
  Reporting for public, industry and government
Life Cycle Cost Analysis (LCCA)

- Need for both pavement and interactions of pavement with users:
  - Performance models
  - Cost data: direct costs and social costs
Four Key Stages of Life Cycle Assessment

1. **Goal Definition and Scope**
   - Define questions to be answered (sustainability goals) and system to be analyzed.

2. **Life Cycle Inventory Assessment**
   - The “accounting” stage where track inputs and outputs from the system.

3. **Impact Assessment**
   - Where results are translated into meaningful environmental and health indicators.

4. **Interpretation**
   - Where the results of the impact assessment are related back the questions asked in the Goal.

**Critical Review**

Figure based on ISO 14040, adopted from Kendall.
Inventories of flows needed for all life cycle stages

M = Materials
E = Energy
W = Waste
P = Pollution
T = Transport

Kendall, A., Keoleian, G. A., 2009
US EPA Impact Assessment Categories
(TRACI – Tool for the Reduction and Assessment of Chemical and other environmental Impacts)

- Global warming
- Stratospheric ozone depletion
- Acidification
- Eutrophication
- Photochemical smog
- Terrestrial toxicity
- Aquatic toxicity
- Human health
- Abiotic resource depletion
- Land use
- Water use

Impacts to people

Impacts to ecosystems

Depletion of resources

From Saboori    Image sources: Google
Pavement Life Cycle Stages

data and performance models
needed for each stage

Materials Acquisition and Production
- Material extraction and production

Construction / Maintenance & Rehabilitation
- Equipment Use
- Transport
- Traffic delay
- Safety
- Rolling resistance
- Flooding
- Etc

Use

End-of-life
- Recycle
- Landfill

From: Kendall et al., 2010
ISO Standards and FHWA Pavement LCA Framework Document

- Search “FHWA pavement LCA framework”
- International Standards Organization (ISO) standards for LCA are generic for all materials
- FHWA guidance specific to pavements published in 2016
Social-LCA for transportation

- Indicators and models being developed
- All indicators being reviewed for equity of transportation investment between poor and rich neighborhoods

<table>
<thead>
<tr>
<th>Selected S-LCA Indicator Category</th>
<th>Selected performance measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jobs</td>
<td>Access to Jobs</td>
</tr>
<tr>
<td></td>
<td>Job Creation</td>
</tr>
<tr>
<td>Accessibility/ Equity</td>
<td>Access to Community Destinations</td>
</tr>
<tr>
<td></td>
<td>Access to School</td>
</tr>
<tr>
<td>Mobility/ connectivity</td>
<td>Average Travel Time</td>
</tr>
<tr>
<td></td>
<td>Average Trip Length</td>
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<tr>
<td></td>
<td>Connectivity Index</td>
</tr>
<tr>
<td></td>
<td>Bike/Pedestrian Delay</td>
</tr>
<tr>
<td>Safety/ public health</td>
<td>Level of Service (bicycle and pedestrian)</td>
</tr>
<tr>
<td></td>
<td>Crashes</td>
</tr>
<tr>
<td></td>
<td>Physical Activity and Health</td>
</tr>
<tr>
<td>Livability</td>
<td>Green Land Consumption</td>
</tr>
<tr>
<td></td>
<td>Street Trees</td>
</tr>
</tbody>
</table>
Pavements = urban hardscape not just roads and streets

- Stormwater management, groundwater infiltration
- Tire pavement noise
- Human thermal comfort
- Pedestrian and bicycle functionality
- Better interaction with urban forestry
Getting to Sustainable Streets

Modal hierarchy & mode share

Sustainable Streets

Ecological Services

Placemaking

From Janet Attarian, 2017
Where can LCA and LCCA be implemented now?

- Pavement management system optimization
  - Condition trigger levels for treatment (timing)
  - Treatment selection
- Pavement planning and design
- Policy evaluation
  - Funding planning for maintenance, rehabilitation
  - Materials changes
  - Construction quality specifications
  - Design methods
Implementation Fundamentals

• Implementation of new technology has not occurred until it is used in every day standard practice

• To achieve implementation requires about:
  – $ 1 of research
  – $ 3 of development
  – $ 6 of support for implementation
    • Tools
    • Piloting
    • Training
    • Support

• All of these are required
Steps in development of pavement LCA, LCCA and S-LCA tools?

• Where are we now for LCCA and LCA?
  – Framework ready
  – Data definitions and models ready
  – Need: better data, more tool development

• Where are we now for S-LCA?
  – Just beginning
Objective: web-based integrated tools for:
- Network
- Concept
- Design

With complete life cycle and regionally applicable data
PMS, LCCA, LCA all need some common data

- Pavement tools need updated data and models, make them web-based, and connected to each other, using same data
  - PMS
  - ME design systems
  - LCCA
  - LCA

- Update information routinely
Caltrans Pavement Engineering and Database/Software Interactions

Databases and Models:
- Caltrans Traffic Census
- Caltrans TSN AADT counts and WIM (PeMS) Database
- Caltrans DRISI GIS LRS Database
- Caltrans Traffic Weigh In Motion Axle Load Spectra Database
- Caltrans As-Builts Cores, GPR Database
- Caltrans Pavement APCS Database
- Caltrans Pavement/ OE Treatment Costs Database
- UCPRC LCA Emissions and Resource Use characterization Factors Database

Software:
- PaveM Pavement Management System
- H-Chart*, RP-List*, PCR* Reporting Programs
- CA4PRS * Construction Productivity Project
- MEPDG Design Program
- CalME * Design Program
- eLCAP * Life Cycle Assessment Program
- Real Cost* Life Cycle Cost Analysis Program

*Software created and/or updated by UCPRC
eLCAP and PaveM
Functionality and Data Sources

**Caltrans Database**
- Traffic
  - Traffic and Flow by Lanes
  - Weigh in Motion (WIM)
- Pavement
  - Network Level Cost
- DRISI
  - Linear Reference System (LRS)

**Software**
- PaveM
  - Network analysis
- eLCAP
  - Conceptual Level Analysis Module
  - Design Level Analysis Module

**Output**
- California Specific Network Level Estimate of GHG and Other Emissions, Resource Use
- California Specific Conceptual Level Estimate of GHG and Other Emissions, Resource Use for PID
- California Specific Project Level Estimate of GHG and Other Emissions, Resource Use for Design

**Input Sources**
- EPDs from industry
- Other inventory data
- Districts/ Pavement
  - Project Design Details From CalMe and MEDG
How to get better regional data for materials: Environmental Product Declaration (EPD)

Environmental Facts
Functional unit: 1 metric ton of asphalt concrete

<table>
<thead>
<tr>
<th>Environmental Impact</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Primary Energy Demand [MJ]</td>
<td>$4.0 \times 10^3$</td>
</tr>
<tr>
<td>Non-renewable [MJ]</td>
<td>$3.9 \times 10^3$</td>
</tr>
<tr>
<td>Renewable [MJ]</td>
<td>$3.5 \times 10^2$</td>
</tr>
<tr>
<td>Global Warming Potential [kg CO$_2$-eq]</td>
<td>79</td>
</tr>
<tr>
<td>Acidification Potential [kg SO$_2$-eq]</td>
<td>0.23</td>
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<tr>
<td>Eutrophication Potential [kg N-eq]</td>
<td>0.012</td>
</tr>
<tr>
<td>Ozone Depletion Potential [kg CFC-11-eq]</td>
<td>$7.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>Smog Potential [kg O$_3$-eq]</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Boundaries: Cradle-to-Gate
Company: XYZ Asphalt
RAP: 10%

Adapted from Pavement Interactive

Example LCA results
Recommended 3 Stage Approach for Implementing EPD Requirements

1. Develop rules and then require reporting, move towards standardization of EPDs (1-2 years)
   - Caltrans will begin requiring EPDs for pavement materials in 2018

2. Develop standardization, rigor, review process, level playing field, appropriate applications (3 to 5 years)
   - Most of Europe has standardized EPD requirements

3. If desirable and have made sufficient progress, consider using for procurement
   - Defining principle: Must take into account equivalent performance
   - Netherlands, France, Sweden are using for selecting contractors
PMB manufacture causes about 60% more air emissions than straight bitumen in Europe;

True in US? Can modified asphalt show more than 60% increase in life?

Eurobitume LCI
Bernard et al. Nantes LCA 2012
## Caltrans Network: Optimal IRI to trigger treatment for GHG by traffic group

<table>
<thead>
<tr>
<th>Daily equivalent vehicles of lane-segments range</th>
<th>Total lane-miles</th>
<th>Percentile of lane-mile</th>
<th>Optimal IRI triggering value m/km, (inch/mile)</th>
<th>Annual CO$_2$-e reductions (MMT)</th>
<th>Modified total cost-effectiveness ($/tCO$_2$-e)</th>
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</thead>
<tbody>
<tr>
<td>&lt;2,517</td>
<td>12,068</td>
<td>&lt;25</td>
<td>-----</td>
<td>0</td>
<td>N/A</td>
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<tr>
<td>2,517 to 11,704</td>
<td>12,068</td>
<td>25-50</td>
<td>2.8 (177)</td>
<td>0.141</td>
<td>1,169</td>
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<tr>
<td>11,704 to 19,108</td>
<td>4,827</td>
<td>50-60</td>
<td>2.0 (127)</td>
<td>0.096</td>
<td>857</td>
</tr>
<tr>
<td>19,108 to 33,908</td>
<td>4,827</td>
<td>60-70</td>
<td>2.0 (127)</td>
<td>0.128</td>
<td>503</td>
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<tr>
<td>33,908 to 64,656</td>
<td>4,827</td>
<td>70-80</td>
<td>1.6 (101)</td>
<td>0.264</td>
<td>516</td>
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<tr>
<td>64,656 to 95,184</td>
<td>4,827</td>
<td>80-90</td>
<td>1.6 (101)</td>
<td>0.297</td>
<td>259</td>
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<tr>
<td>&gt;95,184</td>
<td>4,827</td>
<td>90-100</td>
<td>1.6 (101)</td>
<td>0.45</td>
<td>104</td>
</tr>
</tbody>
</table>

**TOTAL:** 1.38 416

Wang et al 2014
Annual Excess Fuel Consumption from Asphalt Viscoelastic Response Simulation flowchart
Structural Response Simulation Results by factorial traffic/climate (avg ml/km/veh EFC)

Composite flexible

Section

Rigid Composite Flexible Semi-rigid

E[EFCS] (mL/km/veh)

Very low

Section

PD01 PD02 PD03 PD04 PD05 PD06 PD07 PD08 PD09 PD10 PD11 PD12 PD13s1 PD13s2 PD14 PD15 PD16 PD17 PD18s1 PD18s2 PD19 PD20 PD21 PD22s1 PD22s2 PD23

MIT MSU OSU

Very low
Roughness (R) and Macrotexture (M) Simulation Results by Section Specific Data relative to 0.6 m/km and 0.5 mm (avg ml/km/veh EFC)
The Forgotten 80% of Our Pavements

**CENTERLINE MILES**
(in millions)
- 13,537, 8%
- 15,160, 9%
- 65,166, 39%
- 75,208, 44%

**LANE MILES**
(in millions)
- 27,074, 7%
- 50,462, 13%
- 132,804, 35%
- 170,555, 45%

**VEHICLE MILES TRAVELED**
(in millions)
- 657, 0%
- 115,190, 35%
- 180,259, 55%
- 31,414, 10%

National $ Spent on Transportation in 2008 (US Census Bureau)

<table>
<thead>
<tr>
<th>STATE GOVERNMENT</th>
<th>LOCAL GOVERNMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>97,508,989</td>
<td>61,053,150</td>
</tr>
</tbody>
</table>
County LCCA and LCA example: 8% vs 12% air-voids

• Assumptions:
  – Rural pulverize HMA, compact, 4 in. HMA
  – $31/m^2
  – 12% air-voids = 12 year life
  – 8% air-voids = 18 year life

• Net present cost* per ln-mi over 50 year period:
  – 12% air-voids = $2.6 million
  – 8% air-voids = $1.9 million = 29% less cost

• Greenhouse gas emissions are 34% less

*2% discount rate
Effects on greenhouse gas emissions of concrete specifications for concrete cement & SCM content

- Mix designs from a city that hasn’t reviewed specifications and Caltrans heavy duty highway

![Bar chart showing Global Warming Potential (GWP) for different concrete specifications.](chart.png)

- Urban Street - no SCM: 0.159 kg CO2e per 1 kg of PCC
- Playground - no SCM: 0.122 kg CO2e per 1 kg of PCC
- State Highway - 15% SCM: 0.107 kg CO2e per 1 kg of PCC

- 20% less cement
- 33% less cement
- 15% fly ash
- Less shrinkage
To reduce greenhouse gases, California passed a law to make pavements more reflective. Was it the right thing to do? LCA can be used to check policy.
Difference in greenhouse gases for: asphalt inlay vs thin concrete, slurry vs reflective coatings

1A = slurry seal → reflective coating;
2A, 2B, 2C = mill-and-fill AC → no-, low-, or high-SCM BCOA
So what can be done to make pavements more sustainable?

- FHWA Sustainable Pavements Task Group
  - Covers everything about pavement and sustainability
  - Tech briefs and webinars

路面可持续发展参考指南

目录:
高参摘要
第1章 导论
第2章 路面可持续性的概念
第3章 在材料方面提高路面可持续性的考虑
第4章 路面和修复设计对提高可持续性的影响
第5章 建设阶段关于提高路面可持续发展的问题
第6章 运营阶段问题
第7章 提高可持续性的养护维修措施
第8章 报废阶段的考虑
第9章 大系统下的路面可持续发展
第10章 路面可持续性的评估
第11章 结论

How to prioritize what to do?

Bang for your buck metric: $/ton CO₂e vs CO₂e reduction

- Many alternatives to improve sustainability
- Cost from Life Cycle Cost Analysis (LCCA)
- Environment from Life Cycle Assessment (LCA)

Initial Cost

Life Cycle Cost = Initial Cost + Future Cost + Direct Energy Saving Benefits

Adapted from Lutsey, N (2008) Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-08-15
New Caltrans project beginning in 2018

• Calculation of Benefit/Cost for Alternative Strategies to Reduce GHG
  – Evaluate all potential strategies that Caltrans could undertake to improve sustainability, for example
    • Planning
    • Pavement and bridges
    • Equipment
    • Traffic operations
    • Land use for solar, other energy generation
  – Primary focus on greenhouse gases, but also on important local issues: air pollution
All new Caltrans pavement initiatives required to have LCA and LCCA

- Asphalt rubber
  - All Caltrans surfaces must be rubberized, top 60 mm
  - Next: deeper use of gap-graded rubber mixes
- Thin bonded concrete overlay on asphalt
  - 100 to 175 mm concrete overlays bonded to existing asphalt
- PG+X
  - All binders used in dense-graded hot mix to have 5 to 10 percent tire rubber
- High RAP mix
  - 16 to 40 %
  - Interaction with warm mix asphalt
Conclusions

• We must deliver more in terms of sustainability:
  – Cost, safety, smoothness, construction delay, small environmental impacts, local pollution
  – Asphalt paving: compaction, recycling as long as equal or better performance, smoothness

• Deliver innovation that can be used
  – $9 on development, implementation for each $1 of research

• Be using LCA and LCCA now!
  – Optimize pavement management system decision trees
  – Evaluate all new materials and pavement structures as part of research & development process before implementation
  – Evaluate changes in policy, specifications
  – Review and respond to new and automated vehicles
Conclusions

• Put LCA, LCCA and later Social LCA tools into standard practice; next 5 years
  – Finish filling data and model gaps
  – Require EPDs
  – Deliver first generation tools
• Require training in LCA and LCCA for all undergraduate pavement students, starting now
  – Practice as part of their materials design classes
• Train all practicing engineers, pavement managers, decision makers in LCA and LCCA, starting now
• Educate policy-makers on basics of LCA and LCCA and prioritization of policy using them, starting now
LCA Team:

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Arash Saboori
Jon Lea
Jeremy Lea
Changmo Kim
Hui Li
Maryam Ostovar

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