The Role of Life Cycle Assessment in Reducing Greenhouse Gas Emissions from Road Construction and Maintenance

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Introduction

The United States has over 4 million miles of public roads (Federal Highway Administration, FHWA, 2013) and 2.65 million miles of paved roadways[1] (FHWA, 2012), supporting nearly 3 trillion vehicle miles traveled annually (Davis et al., 2014). The nation's roadway system is one part of a transportation network that provides mobility and access to a range of users (e.g., access to schools, services, and work; leisure travel; and general mobility) (FHWA, 2015a). The roadway system is also vital to the economy because it enables the movement of freight and commodities, and is a major source of employment. Roads carry about 65% of all freight in the nation, in terms of both tons and dollar value (BTS/FHWA, 2014). More than 300,000 people were employed in the road and bridge industry in 2014, and even more were employed before recent cuts in transportation infrastructure funding. Most of these jobs do not require a college degree and typically offer higher wages than jobs requiring similar educational backgrounds (Bureau of Labor Statistics, 2014).

However, operation of the nation's pavement network which includes both its construction and its maintenance, is costly. The total annual construction and maintenance expenditure for U.S. highways (pavements and bridges) in 2008 was $135 billion (FHWA, 2008). Highway construction and maintenance also requires large inputs of energy and natural resources, and causes significant emissions of greenhouse gases (GHGs), criteria air pollutants, and water pollutants. Vehicle operation on the nation's roadways consumes more than 169 billion gallons of fuel (FHWA, 2010) and the amount of energy consumed by vehicles is affected by the pavements they roll on.

Taken together, these numbers demonstrate the magnitude of the investment in public roadways, and the system's importance in supporting movement, access, and mobility. At the same time, there is increased recognition of the harm caused by pollutants from roadway construction and demolition of worn-out materials; of the influence of pavement on the fuel use of vehicles and on the surrounding environment; and of the increasing costs of resources. This has led to efforts to understand and mitigate these negative effects. To effectively mitigate a negative environmental effect, the extent of damage must be measured and the source of the damage must be identified. For this reason, it may not be surprising that pavement and pavement materials have been the subject of life cycle assessment (LCA) for nearly two decades.

LCA is a method for determining the environmental sustainability of a product or system by calculating the resource energy flows consumed and the consequent environmental effects from "cradle to grave." When applied correctly to pavement systems, LCA can anticipate unintended consequences of a policy or practice.

[1] This includes only public roads.

When combined with life cycle cost analysis (LCCA), the tool used by pavement managers to determine the cost-effectiveness of different maintenance treatments and their timing, LCA results can be used to find the most cost-effective approaches to reducing environmental impacts. For example, the Netherlands public works agency responsible for roads (Rijkswaterstaat) has gone so far as to routinely select contractors to design and build road construction and rehabilitation projects based on a combination of the projects' life cycle environmental impacts calculated using LCA and life cycle costs calculated using LCCA. The Netherlands performs these calculations using a system named *DuboCalc* (Rijkswaterstaat 2013). This combined approach has created a process that allows industry to compete based on its ability to reduce both the environmental impacts and the costs of projects, presumably leading to cost-effective environmental actions.

The U.S. pavement industry is beginning to develop standardized and transparent methods of reporting the environmental impacts of its products and operations, in part because road owners are creating the demand for high quality and fairly reported information that includes consideration of LCA in project development. For example:

- The Illinois State Toll Highway Authority is developing an LCA system and moving toward incentivizing its use.
- The California Department of Transportation has included network-level GHG LCA equations in its pavement management system (PMS). This inclusion allows Caltrans to evaluate the impacts on global warming potential of different scenarios for its pavement maintenance and rehabilitation operations. For example, vehicles use less fuel when driving on pavement that is in good condition, a factor that needs to be considered along with the impacts of the pavement construction.

Scope of White Paper

This white paper summarizes the state-of-knowledge and state-of-the-art in pavement LCA modeling, with particular emphasis on life cycle GHG emissions and on interpretation and analysis that lead to GHG reductions from the on-road transportation sector. This white paper synthesizes research from a number of previous and current projects, highlighting both broadly agreed upon methods and findings, and those that are emerging or currently debated. The goal is to inform federal, state, and local policymakers; pavement industry professionals; private pavement owners; and transportation and other researchers about the significance and role of pavement LCA in understanding and mitigating the negative environmental consequences of the pavement sector.

LCA Development, Standardization, and Application to Pavement

LCA was developed largely to address questions about consumer products, and over time became a tool for evaluating more complex systems, such as pavement. The International Organization for Standardization (ISO) and a number of other institutional bodies have developed frameworks for LCA (ISO, 2006). Still other bodies have developed frameworks for

standardizing life cycle GHG assessments, or *carbon footprints* (British Standards Institute, 2008). Carbon footprints are a narrow application of LCA principles that consider only one category of pollutant, and thus are not an LCA.

Life cycle based frameworks typically consider a four-phase process consisting of the following:

- **Goal and scope definition**. The goal and scope definition establishes the system to be evaluated and the boundaries of the study.
- **Life cycle inventory (LCI)**. 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.
- **Life cycle impact assessment**. Impact assessment translates the effects of the input and output flows tracked in the LCI into indictors of their effects on humans and the environment. The purpose of impact assessment is to better understand the environmental significance of the LCI by translating environmental flows into environmental impacts. Impacts are presented in different categories that can be broadly grouped into energy use, resource use, emissions, toxicity, and waste generation. Impacts often include eight or more separate impact indicators. Each of these types of impacts can be summarized at a higher level as impacts to people (humans); impacts to nature (ecosystems); and depletion of resources.
- **Interpretation**. Interpretation may occur during all stages, but is perhaps most important after impact assessment, because it will guide the development of conclusions and recommendations based on a study's outcome.

Although LCA guidelines were first established in the 1990s, there remain unsettled questions for how to appropriately apply LCA to long-lived systems with uncertain life cycles, such as pavements. Additionally, challenges remain in how to consider the spatial and temporal heterogeneity of such systems. Early LCAs of pavements focused mostly on material type comparisons, such as comparing asphalt concrete surfaces with portland cement concrete surfaces. These studies often had quite different and limited boundaries of analysis, for example, focusing only on material production and placement, and omitting potentially important effects over the pavement life cycle, or only considering a narrow sub-set of environmental impact categories, such as GHG emissions or energy.

As LCA has matured, so has its application to pavement systems. Starting in the mid-2000s researchers began to consider more of the complexities of pavement design and decisions, such as the effect of pavement management decisions on traffic flow, or the effect of pavement materials on vehicle operation (Santero et al., 2011). In many cases, these studies still sought to compare material types, and examined a single environmental indicator, GHG emissions. In 2010, the University of California Pavement Research Center (UCPRC) convened a Pavement LCA conference in Davis, Calif., to begin the process of standardizing pavement LCA and to build greater understanding of LCA for stakeholders in the pavement sector (Harvey et al., 2010). This conference yielded LCA guidelines tailored to pavements, and led to two more conferences:

2012 in Nantes, France (Ventura and de la Roche 2012); and 2014 in Davis, Calif., (Harvey and Jullién, 2014). In addition, the FHWA has been supporting the dissemination of pavement LCA knowledge and the development of pavement LCA guidelines through its Sustainable Pavements program (FHWA 2015b).

Definition of the Pavement System and Life Cycle

The roadway system and other pavement assets (e.g., parking lots, bike and pedestrian paths) are critical elements of the transportation network. They facilitate movement of freight and commodities, and connect the broader public to services, work, and leisure (FHWA, 2015). Pavements are a major part of the transportation system, and are defined as engineered structures in contact with the earth's surface built to facilitate movement of people and goods. They encompass a wide range of uses and applications (including railways and airfields) but here we consider only pavements used in roadways.

Pavement Life Cycle Stages

The life cycle phases of any pavement can be divided into phases (Figure 1) with all phases affected by decisions at the network management and project design levels:

- **Material production** phase includes raw material acquisition and material processing, as well as materials used in initial construction, and materials used for subsequent maintenance and rehabilitation.
- **Construction, Preservation, Maintenance, and Rehabilitation** phase encompasses the transportation and placement of pavement materials, and construction operations (e.g. equipment use, work zone effects, etc.).
- **Use** phase includes the effects of pavement on vehicles using it and pavement-environment interactions that can affect air, water, thermal and other natural cycles and conditions.
- **End-of-life** phase may apply to an entire pavement system or to a portion of the structure that has failed.

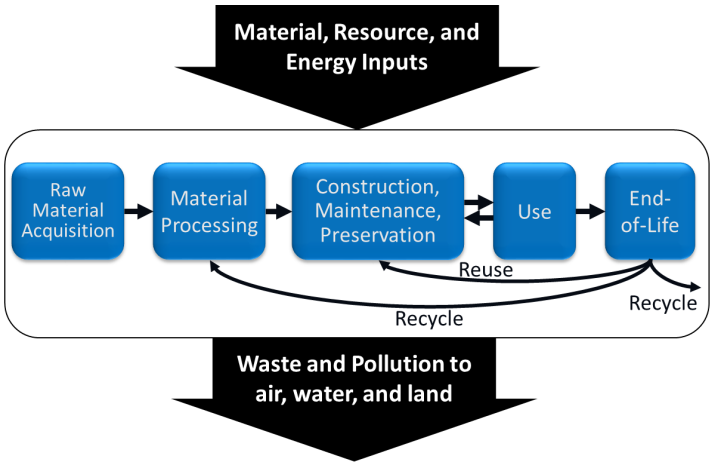

Figure 1. The Pavement Life Cycle

Material Production

The material production phase of a pavement LCA considers each material used in the life cycle. Each material must be characterized by a cradle-to-gate LCI. Cradle-to-gate refers to a partial product life cycle, wherein the "cradle" is the product extraction and the "gate" is the factory gate. Specifically, it refers to the process of raw material acquisition from the ground; mining and crushing of sand and gravel; production of asphalt, cement and other binders; and manufacture of other materials such as additives and steel; transport to, from, and within processing or manufacturing sites; processing and manufacturing of materials; and mixing processes (for materials such as portland cement concrete or hot mix asphalt). One topic of debate for pavements (but a topic which is not typically debated in other LCA applications) is feedstock energy. Feedstock energy is the energy stored in a material, and based on LCA standards, must be included in energy consumption calculations. As a crude oil product, asphalt binder has a large amount of feedstock energy, but this energy is preserved during recycling and is not destroyed when used in asphalt binder. Thus, the pavement LCA guidelines recommend that feedstock energy be reported separately from the energy consumed during acquisition, transport, and processing, as the feedstock energy could be harvested later from the material (and is retained during recycling), while other consumptive energy uses are non-recoverable.

Construction, Preservation, Maintenance, and Rehabilitation

The following stages should be considered for modeling the construction phase and capturing all the energy consumption and environmental impacts in pavement LCA studies (Harvey et al., 2010):

- Equipment mobilization and demobilization (i.e., transport of equipment to and from site).
- Equipment use at the site.

- Transport of materials to the site (including water) and transport of materials from the site (i.e., final disposal, reuse, or recycling of materials).
- Energy used on site (e.g., for lighting if construction occurs at night).
- Changes to roadway traffic flow, including work zone speed changes and delay, and diversions where applicable.

Most studies exclude capital investment, construction of the production plants, and manufacturing of the equipment. This exclusion is an acceptable practice, but should be explicitly stated when describing the scope of analysis. In addition, while maintenance and rehabilitation happens at a different time in the life cycle of a pavement, they are both considered as occurring during the construction phase because the nature of the activities and processes are the same.

Use

The pavement use phase can be broken into two key processes; the travel of vehicles on the pavement, and the interaction of the pavement with the climate and surrounding environment. Pavement characteristics directly affect the use phase impacts through different mechanisms:

- Roughness, structural response under vehicle loads, and macrotexture affect vehicle fuel economy, and can collectively be labeled “pavement rolling resistance” characteristics.
- Surface texture and permeability impact noise generated from tire-pavement interaction.
- Permeability of the pavement system influences storm water runoff and surface friction. Permeable pavement can reduce peak flow rate and affect the pollution and heat flow to receiving water bodies.
- Albedo, heat capacity, and thermal conductivity of the pavement all affect the absorption of energy from the sun and the emission of thermal energy from the pavement, which can potentially cause increases in the temperature of urban areas and increase energy consumption through building and vehicle cooling system use.
- Albedo can also affect energy used for lighting of pavement, where lighting is present.

It should be noted that many of the use phase effects are not well quantified or calibrated and research is still in progress in those areas. Also, as discussed earlier, some impacts are the result of the use phase but are not considered in pavement LCA and are more relevant to a roadway LCA. Human safety impacts must always be balanced with environmental impacts, and there are potential trade-offs between some of the concerns listed above and safety.

End-of-Life

There are three different options available at the end of pavement service life. They include:

- Removal of materials and disposal in landfills,
- Pavement re-use (in place as an underlying layer), or

- Pavement material recycling (either in place or at a recycling plant).

Reusing pavement materials in place and recycling pavement materials from other locations will displace use of virgin aggregates and binders (particularly asphalt, but others as well) and therefore eliminate the impacts of producing virgin materials. However, there are still emissions and energy consumption related to demolition, possible processing, and transport of the recycled materials. To quantify the impacts of recycled materials, information is collected regarding the equipment used and the fuel consumed in processing and transporting the recycled materials. The main challenge in this stage is how to divide the impacts and energy consumption between the original materials production and the re-use of the materials. The division of the impacts between the upstream and downstream projects is called "allocation."

Allocation is also an issue in new materials production and can be particularly challenging where pavement materials are produced from multi-product processes, such as asphalt, which comes from oil refining. Allocation is also challenging where co-products, by-products, and recycled materials come from other industries. ISO recommends avoiding allocation through subdivision of production systems (where the inputs, processes, and sub-processes that comprise the production system are attributed to particular co-products) or through system expansion (where co-products and by-products are modeled to displace similar or substitutable products in the market). When avoiding allocation through subdivision or system expansion is not possible, ISO recommends allocation based on physical properties (e.g. mass, or energy content) or monetary value. Currently there is no consensus on the preferred method of allocation for co-products, by-products, or recycling of materials. It is, however, generally accepted that the allocation method should incentivize practices that reduce environmental impact, prevent double-counting of recycling benefits, provide fairness between industries, and be transparent regarding how the allocation is conducted (FHWA, 2015).

Design decisions for new pavement projects, as well as for maintenance, rehabilitation, and reconstruction projects affect all of these phases, making the pavement design process a key determinant of the pavement LCA. Figure 2 describes the inputs and processes considered at each phase and illustrates how pavement design affects them. The example inputs and processes are not exhaustive, but they provide an indication of the likely scope of a pavement LCA and suggest the kinds of information and data required to conduct an LCA.

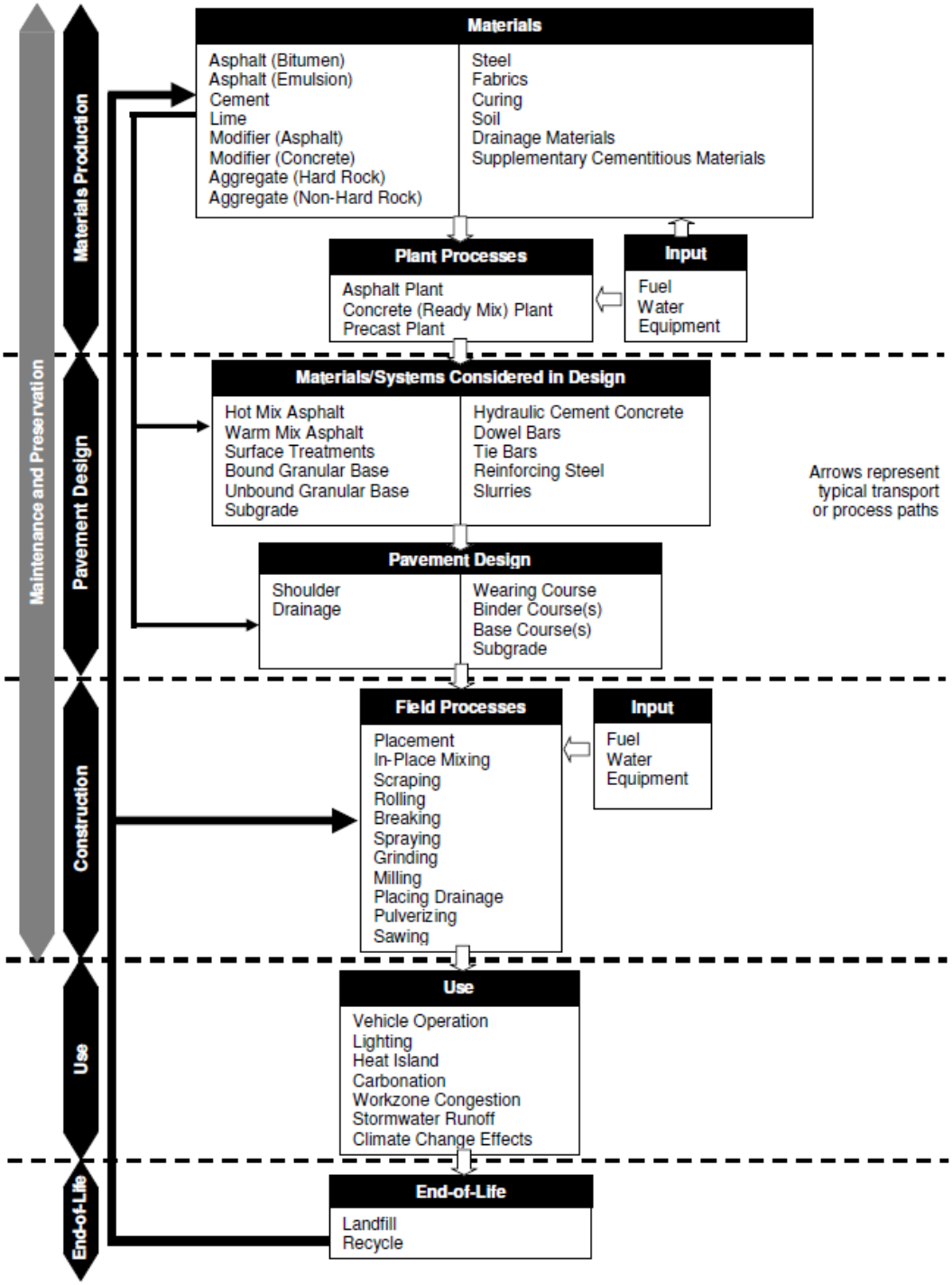

Figure 2. Pavement life cycle phases and consideration of processes within each phase (FHWA, 2014a)

Pavement Questions LCA can Answer

The purpose of an LCA affects the scope of analysis, which in turn affects the results and conclusions. This is reflected by the large variability of results from previous pavement LCAs. LCA has been used to answer many different questions that include the following categories (FHWA, 2014b):

1. Developing a generic framework for new pavement materials, design, construction, and preservation (e.g., Santero et al., 2011, Hendrickson et al. 2007)
2. Comparing the environmental impact of new and rehabilitated pavements (e.g., Santero and Horvath, 2009, Rajendran and Gambatese, 2007)
3. Assessing environmental impacts of recycling (e.g., Ventura et al., 2008, Bartolozzi et al., 2011)
4. Recommending approaches for including LCA in decision-making processes at the network and project levels (e.g., Mukherjee and Cass, 2011, Wang et al., 2012)
5. Considering life cycle costs and environmental impacts together (e.g., Zhang et al., 2010, Gosse and Clarens, 2012)
6. Comparing impact assessment methodologies (e.g., Huang et al., 2013, Kucukvar et al., 2014)
7. Determining the effects of road maintenance for different types of vehicle propulsion in the fleet (e.g., Wang et al., 2012, Yu et al., 2013)
8. Understanding uncertainty from data variability, analysis assumptions, and applications to different kinds of projects (e.g., Chappat and Bilal, 2003, Milachowskl et al., 2011, Noshadravan et al. 2014)

Another important distinction among studies is the choice of environmental impact categories. The most limited studies tend to focus only on energy and GHG emissions. In a recent literature study on pavement LCA (FHWA, 2014b), out of 60 studies, 16 considered both GHG emissions and energy consumption, 13 considered only GHG emissions, and three considered energy alone (making them carbon or energy footprints rather than full LCAs), while 10 studies reported results for a full standard set of impact categories. While carbon and energy footprints have value, they limit the understanding of tradeoffs across impact categories.

Those studies that compared material types (usually asphalt concrete and portland cement concrete) often arrived at conflicting—or more precisely, different—findings that are a function of the modeled system (site and conditions), as well as of the assumptions made and system boundaries of the LCA (Stripple, 2001, Athena Institute, 2006). In fact, the research question itself may have been unsound, since technology and material options are not binomial (concrete or asphalt), but rather should be considered as a spectrum of alternatives within material types and across material types.

Increasingly, LCA methods and consideration of uncertainty and variability in pavement LCA have grown as areas of research. Method-oriented studies attempt to fill a need for guidelines

that are tailored to the topic. In 2010, the UCPRC published an LCA guideline for pavements that has been used by U.S. researchers (Harvey et al, 2010). Studies focusing on modeling uncertainty are a bit different; they may address uncertainty in predicting the actual life cycle stages of pavements (for example, pavement lifetime, deterioration processes, rehabilitation and maintenance timing, and their impacts, etc., e.g. , Xu et al., 2014), or focus on issues that are broadly problematic in LCA, such as the geographic and age appropriateness of data.

Discussion

LCA has become an indispensable tool for guiding pavement engineering and management strategies to reduce environmental impacts. Since LCA considers the full life cycle and full system effects, it plays an essential role in minimizing the risks of unintended consequences and in identifying trade-offs and system-optimal solutions.

Findings

Some pavement LCA findings that can be more readily generalized come from studies that focus on energy and carbon footprints of pavements, as outlined below:

- In general, the scope of a pavement LCA should include all life cycle phases. The influence of different phases on the final interpretation will often depend on which impact indicators are of most interest. The following are examples of this relationship between impact indicators and the life cycle phases:
    - Non-renewable resource use, storm water, and some air pollution impact indicators are mostly affected by the materials production and construction phases.
    - GHG emissions and other impact indicators associated with vehicle fuel use are mostly affected by the use phase, especially for pavements on high traffic volume routes. The effect of a pavement on vehicle operation is a function of the rolling resistance characteristics. In addition, congestion effects and travel speeds through construction work zones may affect vehicle fuel use.
- When the impact indicators of most interest are GHG emissions, the pavement life cycle phases that are most likely to be influential depend on the traffic level. For example:
    - On low traffic volume roads most GHG emissions occur in the materials and construction phases, and in the end-of-life phase if there is removal and transport of materials.
    - On high traffic volume roads the effects of pavement condition and structure on vehicle fuel use have the greatest influence, and can be much greater than the effects of materials production and construction.
- Pavement management practices to keep pavements smooth can produce important reductions in GHG emissions and energy use. For example:
    - The greatest emissions reductions occur when the pavements with the highest traffic levels are kept in very smooth condition. This requires that agency funding is targeted for keeping those sections smooth.

- Pavements with the lowest traffic levels will not produce emissions reductions when kept smoother, and management should focus on preserving the pavement structure.
- Trade-offs between cost, GHG, and energy use reductions can be explicitly evaluated by combining LCA and LCCA, which allows comparisons of investments in pavement smoothness with other investments in the transportation sector and the economy as a whole. Maintaining smoother pavement on the highest volume routes can result in net life cycle cost savings when both the agency and road user costs are considered together with reducing GHG emissions.

- The following pavement considerations affect GHG emissions but are outside of the system boundaries of previous LCA studies:
  - Rough pavement damages freight and agricultural goods, and results in consequential impacts from lost products that have their own life cycle impacts.
  - Maintaining high volume routes in smooth condition also reduces the dynamic interaction between the pavement and truck suspensions. This interaction amplifies the damaging effects of heavy truck axle loads.
- Greater use of recycled materials can often result in reductions in GHG emissions and energy use, particularly when the recycled materials partially replace the typical asphalt and portland cement binders used in pavements. This also is true to a lesser degree when recycled materials replace crushed stone, sand, and gravel. However, increases in life cycle GHG emissions and energy use can occur under certain conditions:
  - If the recycled material is not as durable as the conventional material and results in more frequent maintenance and replacement.
  - If transportation mode (truck, train or marine) and distance, and changes in processing to include recycled materials are not explicitly considered.
  - If inclusion of the recycled material in the current pavement makes future recycling dangerous or prohibitively expensive.

Emerging trends

Emerging trends, issues, and questions that constitute the state-of-the-art for research in the application of pavement LCA are:

- Growing standardization of pavement LCA practice. This has occurred through early critiques of pavement LCA practice (such as by Santero); increasing community discussion through the pavement LCA workshops held in 2010, 2012, and 2014; presentations and discussion in industry meetings and at the Transportation Research Board Annual Meeting; and ongoing meetings and outreach of the FHWA Sustainable Pavements Technical Working Group. The publication of the UCPRC guidelines in 2010 helped start this process, and the expected publication this year of guidelines for pavement LCA by the FHWA will likely accelerate it.

- Development of better inventory data, including the following:
    - A Product Category Rule (PCR) defines how pavement material producers apply LCA to their products. PCRs define the methods for Environmental Product Declarations (EPDs), which report a product-specific cradle-to-gate LCA;
    - However, conflicts can arise between PCRs for pavements and those of industries supplying otherwise unsellable by-products used in pavement. At issue is whether benefits of recycling by-products are allocated to the upstream producer of the by-product, to the downstream user, or to both.
    - EPDs and other data collection efforts underway in North America will improve the availability of life cycle inventory data. Similar efforts are well underway in Europe and Japan, and are beginning in China.
    - The pavement industry in North America is moving towards use of industry-developed software systems for cost-efficient development of EPDs for the multitudes of pavement product variations that come from a given company or plant.
    - Better indications of regional and within-region variability will come from increasing numbers of EPDs for pavement materials and other data collection efforts.
- The pavement industry is rapidly building capacity and transferring knowledge through both industry and federal government initiatives. For widespread implementation to occur, however, more tools need to be developed and knowledge disseminated. In addition, local governments need to be informed about LCA, since they manage approximately two-thirds of the surface area of road pavements in the U.S. Many local government agencies are attempting to improve the environmental sustainability of their pavement networks, but often without access to a sound framework, such as LCA, or high quality information.
- The pavement LCA community is moving away from its previous singular focus on selection of asphalt versus concrete pavement. However, more needs to be done to broaden the uses of pavement LCA. In particular, a number of important questions need to be addressed at the network, urban area, and project levels.
    - Network level questions include:
        - What criteria should trigger maintenance and rehabilitation?
        - How should funding be allocated between maintenance and rehabilitation of pavement versus other transportation investments?
        - What pavement and material types should be used for maintenance and rehabilitation under different situations?
    - Urban area level questions include:

        - What are the heat island effects of alternative pavement systems? Answering this question requires integrating regional climate and building heating/cooling/lighting energy use modeling into pavement LCA.
        - What are the water cycle effects of pavement, and what are the different effects caused by impervious and pervious pavements?
        - What is the interaction between pavement and the urban tree canopy (i.e., shading effects, water access, and root damage)?
    - Project level questions include:
        - What are environmentally preferable recycling strategies and in what situations?
        - What pavement and rehabilitation types perform best for a given situation?
        - What is the optimal design life?
        - What are environmentally optimal construction windows, particularly when traffic delay is considered?

New materials, new structures, and new construction approaches include the following:

- There are moves towards "eco-labeling" of pavement products to provide greater awareness of the environmental impacts of pavement materials in Europe, and awareness of this is increasing in North America.
    - Northern European countries are slowly moving towards consideration of LCA results in the procurement of design-build and design-build-maintain contractors for pavement works and maintenance. This practice was started by the Netherlands, followed by France, and Sweden is expected to move in this direction in the near future. There is some awareness of these developments in the U.S., however, most pavement work in this country is procured through design-bid-build contracts based solely on the lowest-cost bid.

Major gaps exist in current knowledge, particularly lack of well validated and calibrated models in some areas, including:

- Vehicle energy consumption through pavement structural response (current models need calibration); under wet pavement conditions (not yet modeled); and for electric and hybrid vehicles (not yet modeled).
- Net effects of pavement changes to reduce urban heat island effects for different climates and urban architectures (models are currently being developed); and radiative forcing are major areas of uncertainty in climate modeling.
- Human, ecological, and resource use impact models that are regionally applicable and well-calibrated.
- Continued need for pavement performance models for replacement frequency and evolution of pavement roughness and texture.

Policy Recommendations and Conclusions

LCA has demonstrated its usefulness and largely untapped potential for quantifying the environmental impacts of pavement decisions at the policy, network, urban area, and project levels. Although there are gaps that can and need to be overcome, LCA can support the move from discussion of pavement system sustainability in broad, general, qualitative, and largely unverifiable terms to discussion of well-defined, specific, quantitative, and verifiable measurements and calculations.

Government, especially at the state and local levels, can play a role in encouraging and facilitating an active and comprehensive market for LCA data through PCRs and widespread creation of EPDs through their procurement processes and specifications. The federal government (or state and local government in the absence of federal action) has a role in establishing model policies and regulating conflicts between PCRs. The federal government also has a role in supporting its initiatives in establishing low-cost databases for LCA.

The following are recommendations for applying LCA to policy:

- The federal government should standardize pavement LCA and develop requirements for pavement LCA practitioners. State and local government and private pavement owners can require material producers and contractors to follow FHWA guidelines even if the FHWA guidelines are not mandatory. If there is no federal action, leading state and local governments can produce and require standards and requirements, although there is the risk of conflict between different standards. Compliance with ISO standards (which are not specific to pavement) will result in greater compatibility across all industrial products, and across international boundaries in North America, which is important considering the existing movement of pavement materials across borders and between the pavement industry and other industries.
- State and local government should integrate LCA and LCCA into mechanistic-empirical pavement design at the project level and in simplified form in PMS at the network level.
- Use both LCA and LCCA for developing federal, state and local policies that apply to pavements at the project or network level.
- Encourage and facilitate an active and comprehensive market for LCA data through the use of regulated PCRs and widespread creation of EPDs and the support of national and regional not-for-profit databases:
    - Federal and/or state support for the U.S. Life Cycle Inventory (USLCI) database and other databases which will result in greater access to low- or no-cost high quality data.
    - Incorporate strict requirements for third-party review to ensure transparency and rigor, to confirm no conflicts of interest, and to consider impacts on all stakeholders.
    - Designate an authority and establish guidelines to resolve “double counting” in PCRs between industries, which would be best at the federal level, but can be done at the state level if there is no federal action.

    - Encourage, facilitate, and create incentives for new ideas and strategies that reduce the cost and increase the availability of high-quality data.
- Include in future federal transportation legislation requirements that pavement owning agencies benchmark and document their environmental performance, in a manner similar to MAP-21 requirements for benchmarking of pavement condition by agencies that receive federal funding.
- Move toward requirements for EPDs for construction materials.
- Develop approaches for consideration of LCA as part of procurement.
- Continuously improve LCA for pavements by:
    - Normalizing impact indicators to regional environments and human habitats
    - Considering trade-offs between the cost and environmental impacts of pavement decisions
- Include environmental impact performance measures in legislation concerning pavements, and establish LCA as a likely tool for estimating impacts. Performance-based legislation is in contrast to prescriptive legislation that mandates technologies and approaches. Prescriptive legislation can stifle innovation, and may produce negative unintended consequences because they have not been subjected to LCA with broad system boundaries. To be able to use performance-based decision making, the metrics must be relevant to the goals of the organization and its stakeholders, and the methods of preparing the metrics need to be transparent and within the capabilities and budgets of the road owning agencies. This is the goal of current pavement LCA research.

References

Athena Institute (Athena). 2006. A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential. Athena Institute, Ontario, Canada.

Bartolozzi, I., F. Rizzi, A. Borghini, and M. Frey. 2011. "Life Cycle Assessment of Rubberized Asphalt Road Pavement in Lamia, Greece." Proceedings of the 3rd International CEMEPE & SECOTOX Conference. EnviTech.

British Standards Institution. 2008. PAS2050:2008 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. London, UK: http://shop.bsigroup.com/en/Browse-by-Sector/Energy--Utilities/PAS-2050/

Bureau of Labor Statistics. 2014. May 2014 National Industry-Specific Occupational Employment and Wage Estimates, NAICS 237300 - Highway, Street, and Bridge Construction. Department of Labor, Washington, DC. (Accessed May 4, 2015 from http://www.bls.gov/oes/current/naics4_237300.htm#startcontent)

Bureau of Transportation Statistics and Federal Highway Administration. 2014. Freight Facts and Figures 2013. FHWA-HOP-14-004. Washington, DC. January. (Accessed on May 5, 2015 from http://www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/docs/13factsfigures/pdfs/fff2013_highres.pdf)

Chappat, M. and J. Bilal. 2003. Sustainable Development. The Environmental Road of the Future: Life Cycle Analysis. COLAS Group, France.

Davis, S. C., Diegel, S. W., & Boundy, R. G. 2014. "Transportation energy data book: Edition 33: United States". Department of Energy.

Federal Highway Administration (FHWA). 2010. Highway Statistics 2008. Federal Highway Administration, Washington, DC. (Accessed on May 5, 2015 from http://www.fhwa.dot.gov/policyinformation/statistics/2008/pdf/pt3c.pdf)

Federal Highway Administration. 2012. "Highway Statistics". Federal Highway Administration.

Federal Highway Administration. 2013. 2013 Pocket Guide to Transportation. Federal Highway Administration, Washington, DC.

Federal Highway Administration. 2014a. "Development of a Pavement Life Cycle Assessment (LCA) Framework: Synthesis and Literature Review". Federal Highway Administration.

Federal Highway Administration. 2014b. "Tech Brief: Life Cycle Assessment of Pavements" FHWA-HIF-15-001, February. (Accessed March 12 2015 from http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=935)

Federal Highway Administration. 2015a. "Towards Sustainable Pavement Systems: A Reference Document". FHWA-HIF-15-002, February. (Accessed March 12 2015 from http://www.fhwa.dot.gov/pavement/sustainability/ref_doc.cfm)

Federal Highway Administration Sustainability Program. 2015b. (Accessed March 12 2015, from http://www.fhwa.dot.gov/pavement/sustainability/)

Gosse, C. A. and A. F. Clarens. 2012. Network Aspects of Pavement Management Optimization using Life Cycle Assessment. University of Virginia, Charlottesville, VA.

Harvey, J., A. Kendall, I. S. Lee, N. Santero, T. Van Dam, and T. Wang. 2010. Pavement Life Cycle Assessment Workshop: Discussion Summary and Guidelines. UCPRC-TM-2010-03. University of California, Davis, CA. (Accessed March 12 2015 from http://www.ucprc.ucdavis.edu/PDF/UCPRC-TM-2010-03.pdf)

Harvey, J. and A. Jullién. 2014. International Symposium on Pavement LCA 2014. (Accessed March 2015 from http://www.ucprc.ucdavis.edu/p-lca2014/)

Hendrickson, C. T., A. Horvath, S. Joshi, M. Klausner, L. B. Lave, and F. C. McMichael. 1997. "Comparing Two Life Cycle Assessment Approaches: A Process Model vs. Economic Input-Output-Based Assessment." Electronics and the Environment. ISEE.

Huang, Y., A. Spray, and T. Parry. 2013. "Sensitivity Analysis of Methodological Choices in Road Pavement LCA." The International Journal of Life Cycle Assessment. Volume 18, Issue 1. Springer.

ISO. 2006. "14040: 2006 Environmental management – Life cycle assessment – Principles and framework". International Organization for Standardization.

Milachowskl, C., T. Stengel, and C. Gehlen. 2011. Life Cycle Assessment for Road Construction and Use. European Concrete Paving Association, Germany.

Mukherjee, A. and D. Cass. 2011. Carbon Footprint for HMA and PCC Pavements. Report RC-1553. Michigan Department of Transportation, Lansing, MI.

Noshadravan, A., M. Wildnauer, J. Gregory and R. Kirchain. 2013. Comparative Pavement Life Cycle Assessment with Parameter Uncertainty. Transportation Research Part D 25, 131–138.

Rajendran, S. and J. A. Gambatese. 2007. "Solid Waste Generation in Asphalt and Reinforced Concrete Roadway Life Cycles." Journal of Infrastructure Systems. Volume 13, No. 2. American Society of Civil Engineers, Reston, VA.

Santero, N. and A. Horvath. 2009. "Global Warming Potential of Pavements." Environmental Research Letters. Volume 4, No. 3. IOP Science, Philadelphia, PA.

Santero, N., E. Masanet, and A. Horvath. 2011. "Life-cycle assessment of pavements. Part I: Critical review". Resources, Conservation and Recycling, 55(9), 801-809.

Stripple, H. 2001. "Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis." Second Revised Edition. *IVL Rapport*. Issue 1210. VTI, Linköping, Sweden.

Rijkswaterstaat. 2013. "DuboCalc." Rijkswaterstaat – Ministry of Infrastructure and the Environment, Rijswijk, The Netherlands. http://www.rijkswaterstaat.nl/zakelijk/duurzaam/duurzaam_inkopen/duurzaamheid_bij_contracten_en_aanbestedingen/dubocalc/index.aspx

Ventura, A., P. Monéron, and A. Jullién. 2008. "Environmental Impact of a Binding Course Pavement Section, with Asphalt Recycled at Varying Rates: use of Life Cycle Methodology." Road Materials and Pavement Design. Volume 9, Supplement 1. Taylor & Francis.

Ventura, A. and C. de la Roche. 2012. Life Cycle Assessment and Construction, Civil Engineering and Buildings. 2012. Nantes, France (Accessed March 12 2015 from http://lca-construction2012.ifsttar.fr/)

Wang, T., I. S. Lee, J. T. Harvey, A. Kendall, E. B. Lee, and C. Kim. 2012. UCPRC Life Cycle Assessment Methodology and Initial Case Studies on Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance. UCPRC-RR-2012-02. Davis and Berkeley, CA. (Accessed March 12 2015 from http://www.ucprc.ucdavis.edu/PDF/UCPRC-RR-2012-02.pdf)

Xu, X., A. Noshadravan, J. Gregory and R. Kirchain. 2014. Scenario Analysis of Comparative Pavement Life Cycle Assessment Using a Probabilistic Approach. International Symposium on Pavement LCA 2014, Davis, California, October 14-16.

Yu, B., Q. Lu, and J. Xu. 2013. "An Improved Pavement Maintenance Optimization Methodology: Integrating LCA and LCCA." Transportation Research Part A: Policy and Practice. Volume 55. Elsevier, Philadelphia, PA.

Zhang, H., G. A. Keoleian, M. D. Lepech, and A. Kendall. 2010. "Life-Cycle Optimization of Pavement Overlay Systems." Journal of Infrastructure Systems. Volume 16, Issue 4. American Society of Civil Engineers, Reston, VA.