TechBrief

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LIFE CYCLE ASSESSMENT OF PAVEMENTS

INTRODUCTION

An ever-growing number of agencies, companies, organizations, institutes, and governing bodies are embracing principles of sustainability in managing their activities and conducting business. This approach focuses on the overarching goal of emphasizing key life cycle economic, environmental, and social factors in the decision-making process. Sustainability considerations are not new, and in fact have often been considered indirectly or informally, but in recent years increased efforts are being made to quantify sustainability effects and to incorporate them into the decision-making process in a more systematic and organized fashion.

One instrument that can be used to quantify the environmental performance of sustainability considerations is life cycle assessment (LCA). LCA is a structured methodology that quantifies environmental impacts over the full life cycle of a product or system, including impacts that occur throughout the supply chain. The purpose of this Tech Brief is to describe LCA principles, define the main elements of LCA, and provide an introductory overview of how LCA may be applied to pavements.

ORIGIN, PRINCIPLES AND PURPOSE OF LCA

Origin of LCA

The precursors to LCA were originally developed in the late 1960s to analyze air, land, and water emissions from solid wastes. The principles were later broadened to include energy, resource use, and chemical emissions, with a focus on consumer products and product packaging rather than complex infrastructure systems (Hunt and Franklin 1996; Guinée 2012). Between 1990 and 2000, developments shifted to the creation of full-fledged impact assessment methods and the standardization of methods by the International Organization for Standardization (ISO) (SAIC 2006). In the transportation area, LCA topics have included assessing asphalt binder and cement production, evaluating low carbon fuel standards for on-road vehicles, examination of transportation networks, and examination of interactions between transportation infrastructure, vehicles, and human behavior.

Principles and Purpose of LCA

LCA provides a comprehensive approach to evaluating the total environmental burden of a particular product (such as a ton of aggregate) or more complex systems of products or processes (such as a transportation facility or network), examining all the inputs and outputs over its life cycle, from raw material production to the end of the product's life. A generic model of the life cycle of a product for LCA is shown in figure 1. As can be seen, the life cycle begins at the acquisition of raw materials, proceeds through several distinct stages including material processing, manufacturing, use, and terminates at the end-of-life (EOL).

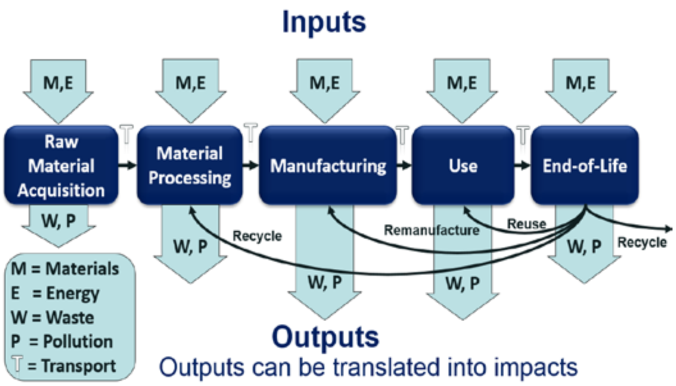

Figure 1. Generic life cycle of a production system for LCA (Kendall 2012).

LCA also accounts for transportation between stages. This definition of the life cycle is often called "cradle to grave." LCAs that do not consider the use or EOL stages are often referred to as "cradle to gate." As illustrated in figure 1, the EOL can include recycling within the product life cycle, remanufacturing, re-use without reprocessing, or recycling into the life cycles of other products. The LCA model tracks materials and energy as inputs to each of these "stages" while tracking waste and pollution as outputs. These outputs can be translated into environmental and social impacts.

LCA can be used for a variety of purposes, including:

- Identifying opportunities to improve the environmental performance of products and production systems at various points in their life cycle.
- Informing and guiding decision makers in industry, government, and non-governmental organizations as part of strategic planning, priority setting, product or process design selection, and redesign.
- Developing appropriate indicators of environmental performance of a product or production system; for example, to implement an eco-labeling scheme (see EPA 2014; EC 2011), to make an environmental claim, or to produce an environmental product declaration (EPD), which is described later.

Moreover, LCA can be used to identify trade-offs in decision making as it allows for the evaluation of all life cycle stages and multiple environmental indicators. If not all life cycle stages are included, or if not all appropriate environmental indicators are studied, then policies, regulations, and specifications intended to reduce environmental impacts from systems may have the risk of unintended negative consequences; this risk is greatest when changes are made to one part of a system or life cycle stage, but the effects of the changes on the rest of the system and the other life cycle stages are not evaluated. When properly applied, LCA is an approach for investigating the consequences of changes that considers system-wide effects and the entire life cycle.

The application of LCA to pavement in the U.S. is still in its early stages, and there are a number of uncertainties in the data and details of approaches that remain to be addressed as its use and application evolves.

LCA STANDARDS

The need to standardize the LCA methodology to ensure consistency in the process led to the development of the LCA standards in the International Standards Organization (ISO) 14000 series (SAIC 2006). Publication of the initial ISO standards in 1997 resulted in a commonly accepted standard method for LCA (delineated by ISO 14040 and 14044 [ISO 2006a; ISO 2006b]); however, specifics vary greatly from one application to another. Attempts at standardizing the LCA procedure for pavements have been made (e.g., UCPRC 2010a), but there are currently no government-issued guidelines in North America on the use of LCA for pavement.

Phases in an LCA

As described in the ISO standards, there are four phases in an LCA study. These phases—Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation—are depicted in figure 2 to illustrate the interaction between these phases.

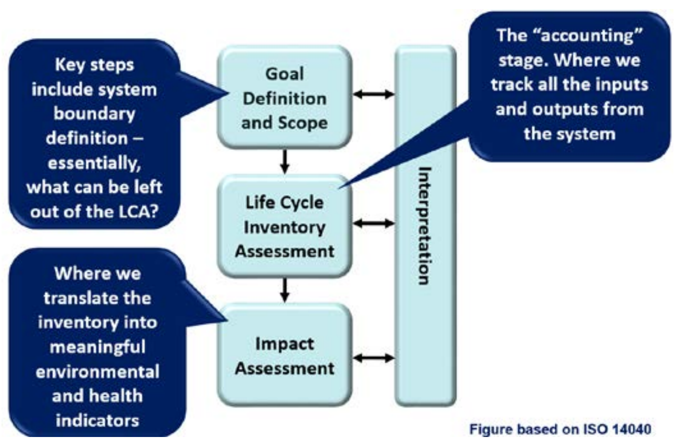

Figure 2. Life cycle assessment framework (Kendall 2012).

Goal and Scope Definition

The first phase in an LCA is to determine its goal and scope. Goals will differ between agencies depending on their overall environmental objectives, policies, laws and regulations, all of which should be based on the environmental values of the agency that produces them. Goals must be set by the organization performing the LCA in order to determine the type of study, the scope, and the approach for assessing impacts and making decisions. It is possible that some goals may conflict with one another.

LCA Terminology

Some important terms defined by ISO (2006a) are summarized below:

Functional Unit *– the unit for which the results of an LCA are reported. A functional unit provides a reference to which the input and output data are normalized. It needs to be clearly defined and measurable. Comparisons can only be made for results expressed in the same functional unit. A typical pavement LCA unit is one lane-mile of a given pavement structure with its associated traffic, climate, etc.*

Environmental Impact Category *– Type of environmental concern for which life cycle inventory analysis results (inputs from nature and output flows to nature such as extraction of material and energy resources, emissions to air, water and land and final waste) may be assigned. The selection of impact categories is important as it defines which environmental considerations are going to be addressed.*

Feedstock Energy *– Heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value. This is an important term when dealing with asphalt binder as it is oil based but not used as a fuel.*

Allocation *– Partitioning environmental flows between the product system under study and one or more other product systems. This is most relevant for valuing the production and use of recycled, co-product, and waste materials (RCWMs) in pavement LCA.*

The scope of an LCA defines the system boundary of analysis (essentially what life-cycle stages and processes are included in the LCA), establishes the geographic and temporal boundaries of analysis, describes the functional unit of analysis, and determines the required quality of data. Again, all of these depend on the subject and the intended use of the LCA. The goal and scope definition determines key features of the analysis, including the depth and the breadth of the study, which can vary depending on the overall goal.

The analysis period defines the period over which the pavement is assessed. It should typically be a function of the studied system, and the analysis period should be 1 to 1.5 times the longest life among compared systems. If the LCA examines a particular pavement design or rehabilitation process, then the time to the next rehabilitation or reconstruction of equal or greater scale intensity may be one way to identify the life used to determine the analysis period, with different approaches available for comparing alternatives with large differences in their lives. For example, a 50- to 60-year analysis period may be appropriate for evaluation of a new pavement alternative whereas 20 years might be quite acceptable for evaluation of rehabilitation strategies. Selection of the analysis period is important because of changes in pavement design, vehicle technologies, energy sources and traffic volume and composition over time. Most LCA studies assume current technologies and practices are modeled forward and remain somewhat constant over time.

Inventory Analysis

The inventory analysis phase is where environmental flows (inputs of material, energy, and resources, and outputs of waste, pollution, and co-products) are tracked for the system being studied. To perform an inventory analysis, a model of the process being analyzed is set up, with definitions of the functional unit and system boundaries. The flows of materials and energy into the process model are then identified and calculated (for example, "Material Processing" in figure 1), as are the waste and pollution flows coming out of the process. The data that are developed for the process are the life cycle inventory (LCI). For a typical asphalt or concrete plant, flows include the use of electricity and fuel oil or natural gas; the use of aggregates, binder, and water; and the waste flow such as emissions and other waste per mix design. The LCI for these are referred to as primary, or foreground, data sources. Primary data are typically collected with as much specific data as possible. All of these have to be traced back to the origin, which are referred to as background data processes. For aggregates this is the quarry processes, for natural gas they are the processes of setting up the gas well and delivering the gas, and so on.

Regarding the development of regionally applicable data, there are several approaches, including assembling existing public source data, purchasing commercially available data and applying appropriate regional and temporal corrections, or directly collecting data. In practice, a combination of these approaches is often necessary. Some examples of approaches to data collection are included in recent literature (e.g., Weiland and Muench 2010; Mukherjee, Stawowy, and Cass 2013; Santero et al. 2011; Wang et al. 2012).

Commercially available LCI databases are updated periodically based on the development of specific LCA studies. That being said, the data requirements—and hence the need for regional data—are tied to the goal and scope of the LCA. No matter what data are used, it is important to report the type of data and their quality in order to identify which data are influencing the conclusions of the assessment, and to perform sensitivity analysis on those inventory datasets that are the most influential. General guidance on data quality and data quality indicators is available from ISO (2006a; 2006b).

Impact Assessment

The purpose of the third phase of the LCA, impact assessment, is to better understand the environmental significance of the LCI by translating environmental flows into environmental impacts that are presented in different impact categories, typically in terms of:

- Impacts on people (humans).
- Impacts on nature (ecosystems).
- Depletion of resources.

LCA studies usually include a selection of impact categories that are most relevant to the specific project goal and scope, and can range from narrowly focusing on energy and greenhouse gas emissions to a broader set of impact categories. The most commonly used selection of impact categories in the U.S. is the TRACI impact assessment methodology developed by the EPA, the most recent version (TRACI v2.0) of which was released in 2012 (Bare 2011; EPA 2012). The most widely used impact assessment method world-wide is the CML methodology (Guinée et.al. 2002), with the most recent update from April 2013. The TRACI and CML categories largely overlap. A list of typical impact categories is shown in table 1.

Table 1. Typical LCA impact categories.

Group	Impact Categories
Energy use	Fuel: non-renewable, renewable
Resource use	Resources: non-renewable, renewable
Emissions	Climate Change Ozone layer depletion Acidification Tropospheric Ozone Eutrophication
Toxicity	Human toxicity: respiratory, carcinogenic, non-carcinogenic Ecotoxicity: fresh water, marine water, soil
Water	Fresh water use
Waste	Hazardous, Non-hazardous

Interpretation and Transparency

General Considerations

In the interpretation phase, the overall results are summarized and discussed as a basis for conclusions, recommendations, and decision making in accordance with the goal and scope definition. Proper LCA practice includes an interpretation where the results are presented for the functional unit, the major contributions are identified and explained in terms of where the impacts are pronounced, the data uncertainty and variations are noted, and sensitivity analyses are conducted for the most important methodological assumptions.

Uncertainty in LCA comes from data variability, input uncertainty, and model imprecision (ISO 2006b). Pavement LCAs should include an analysis of uncertainty in the functional unit, analysis period, LCI data, system boundary assumptions, and impact assessment. Some examples of uncertainty include limitations in the data used, uncertainty in predicting future changes in traffic and technology, and allocation (discussed later) of impacts for recycled materials.

ISO 14044 states that the most important aim of LCA studies is that they be reported transparently so readers can review the goals, scope, and conclusions of the study. ISO 14044 also requires an independent review for LCA studies that compare alternatives, and a review panel is typically convened for that purpose.

Product Category Rules and Environmental Product Declarations

Detailed reporting frameworks for LCA are used in the development of an environmental product declaration (EPD), which is essentially a declared LCA for a product. Somewhat akin to nutritional labels, EPDs present key environmental impact data in a clear and concise fashion that allows for ready comparisons. In the development of the EPD, a review is performed in accordance with the related product category rule (PCR) document, although assumptions allowed in the PCR can still introduce variability. EPDs for some pavement materials are under development, and in the next several years it is expected that EPDs for the main pavement material constituents (e.g., aggregate, cement, asphalt binder, co-products, admixtures, additives, sealants, dowel bars, geotextiles, reinforcing steel) will become available. Eventually, it is likely that EPDs will be developed for materials that are made from various combinations of these constituents, or even for complete pavement structures (most likely only in the design-build or design-build-operate project delivery schemes).

Key Challenges for Pavement LCA

Some of the key challenges identified for the practical use of LCA, written for buildings but currently applicable to pavements, include (Georgia Tech 2010):

- Data collection, including the availability of readily accessible, complete, and regionally/temporally applicable data, and the cost of data collection.
- Data quality, including establishment of standards for collecting, reporting, and allocation of data.
- Issues with impact assessment methods, including consistency and updating of impact assessment methods as understanding of impacts evolves. For example, impacts such as global climate change and ozone depletion are estimated based on internationally established methods, while methods for other impact categories are less consistent.

- Issues with weighting of impacts in decision-making, with the influence of different impact categories on final decisions left to the users. This can be confusing when many impacts are considered in the final decision process, and also when different alternatives have conflicting impact rankings.

Product Category Rules

A Product Category Rule (PCR) document defines the rules for a product LCA and defines the Environmental Product Declaration (EPD) format. The PCR is developed through a formal process that involves all stakeholders (e.g., producers, purchasers, regulators) and is owned and managed by the Program Operator.

Environmental Product Declarations

An EPD, as defined in the ISO 14025 standard (ISO 2006c), is a declared LCA for a product and is a form of certification. EPDs can be issued on a specific product from a specific producer, but may also be issued for a generic product from a group of manufacturers (such as an association).

The basis for performing the LCA to produce an EPD is the PCR, described above. An independent third party performs a verification of the LCA and EPD, after which the Program Operator issues the EPD if it complies with the PCR.

If all pavement products had EPDs based on well-designed PCRs, pavement LCA would benefit tremendously in terms of improved quality and reduced cost.

PAVEMENT LIFE-CYCLE STAGES

The pavement life cycle includes the material production, design, construction (which includes new construction as well as preservation, maintenance, and rehabilitation), use, and end-of-life stages. Pavement design plays a unique role, as it determines the materials used, the pavement structure, future preservation, maintenance and rehabilitation activities, and pavement longevity. These stages and some typical inputs and outputs for pavement are shown in figure 3, with additional discussion provided in the following sections.

Material Production

Broadly speaking, modeling the material production stage requires that each material input to the pavement system be characterized by an LCI that includes the following processes: raw material acquisition, material production (all transformation processes from raw material to product), mixing processes (for example, in asphalt or concrete plants), and transportation of raw or finished materials between stages. As is expected in all LCAs, the inputs to these processes should each be modeled from a life-cycle perspective and should include the background processes (i.e., in addition to accounting for the foreground process of direct energy consumption, the LCI of the background processes for the production of the energy should be included).

Construction, Preservation, Maintenance, and Rehabilitation

The modeling of these stages requires that the following processes be considered: equipment mobilization and demobilization (transport of equipment to and from site); equipment use at the site; transport of materials to the site, including water; transport of materials from the site for final disposal, reuse, or recycling; energy used on site (e.g., lighting for nighttime construction); and changes to traffic flow, including work zone speed changes and delay and diversions where applicable. In addition, changes to traffic over time should be considered, if not in the baseline modeling then in a sensitivity analysis. These changes should include traffic growth and changes to fleet composition (vehicle type mix and technology) (UCPRC 2010a). Many studies exclude equipment manufacturing and capital investments in construction-related production facilities. That is an acceptable practice, but its exclusion or inclusion must be explicitly stated.

Use

Figure 4 indicates various pavement characteristics and their impacts on the use stage, many of which are the focus of current research. These characteristics and their effects are summarized below:

- Pavement roughness, macrotexture, and structural response all can affect vehicle fuel economy, and as a result have significant environmental impacts.
- Pavement surface texture, permeability, and other characteristics affect noise generated from the tire-pavement interaction. This may impact humans both in vehicles and within the acoustical range of the vehicles operating on the pavement. In addition, surface texture and permeability affect surface friction and hydroplaning, which in turn can influence pavement safety.
- The permeability of the pavement system influences stormwater runoff and surface friction. Pavements that are partially or fully permeable can reduce the peak flow rate by holding precipitation within the pavement and slowly releasing it to the environment. This can also affect pollution flow into receiving water bodies and the resultant temperatures of those waters.

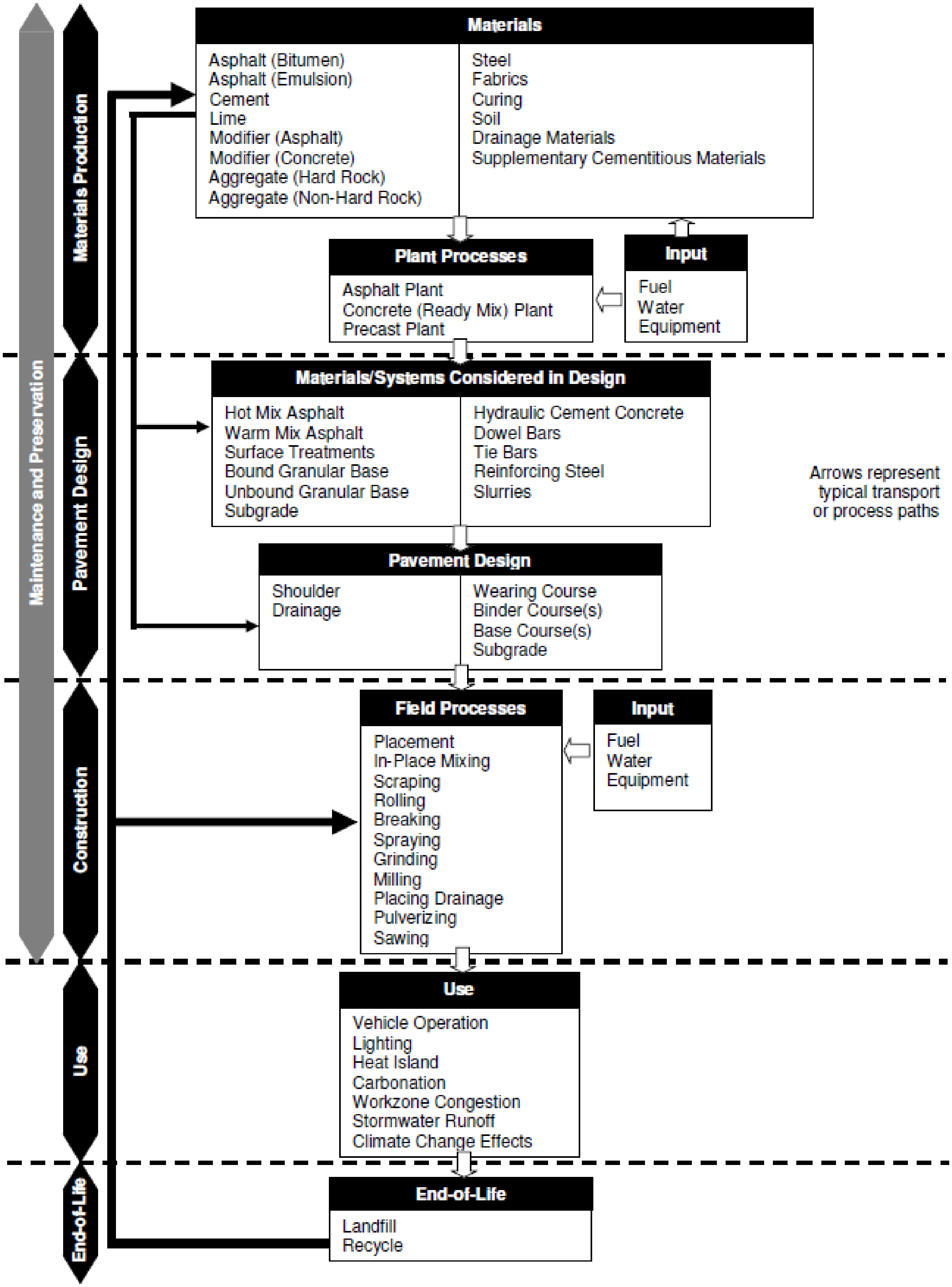

Figure 3. Pavement life-cycle stages (UCPRC 2010a).

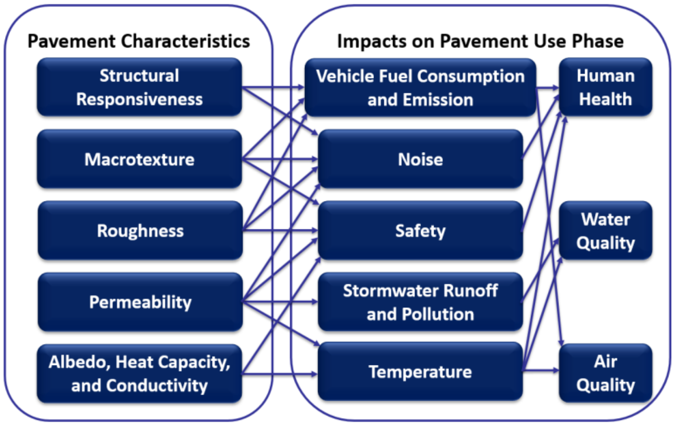

Figure 4. Pavement characteristics and influences on use-stage objective.

- The albedo (reflectance), heat capacity, and thermal conductivity of the pavement all can affect the absorption of energy from the sun and the emission of reflected and thermal energy from the pavement, which can potentially have both negative and positive impacts on energy consumption through building and vehicle cooling/heating systems, air quality, and human health (depending on a number of factors). For some applications, the albedo of the pavement may also have an impact on the energy needed for lighting for nighttime safety and the visibility of pavement markings.

There are trade-offs that must be considered within many of these decisions, including important safety issues. It must be recognized that many of the use stage effects are not currently well quantified and thus considerable uncertainty exists, particularly when considered over long analysis periods (50 years or more).

End-of-Life

Often during rehabilitation, as well as full reconstruction at EOL, materials become available for recycling and reuse (or for disposal). Just as in the other life-cycle stages, information is collected for equipment use and related fuel consumption, the reuse of materials, and the "production" of reused materials like reclaimed asphalt pavement (RAP) or recycled concrete. These materials are typically used in new pavement construction projects either in the base or the pavement layers. In rare circumstances, materials may be transported to a landfill.

In LCA, this poses a challenge in how to partition impacts and benefits to the originating pavement project and the receiving pavement project, with the process of partitioning impacts referred to as "allocation." One example is the partitioning of the benefits associated with the use of RAP, which can be used in significant quantities to replace aggregate and binder in new asphalt pavement. In this case, the question arises as to how much of the environmental benefit is allocated to the older pavement (or to the industry producing the waste) and how much to the new pavement being constructed. Moreover, allocation issues also transcend across industries; for example, the use of fly ash is a "waste" generated from the burning of coal in electrical power plants yet is a desirable cementitious material used to replace portland cement in concrete.

Although there are several methods of allocation, there is currently no consensus on how to perform these allocations for the recycling of pavement materials. A general consensus among LCA practitioners and those involved in evaluating products and systems is that the allocation rules should be set up to address the following:

- Incentivize practices that reduce environmental impact.
- Prevent double counting of credits or the omission of important items.
- Provide fairness between industries by reflecting as closely as possible what is actually happening.
- Be transparent so that all parties can understand how allocation is applied and how it influences the results.

MOVING FORWARD WITH A PAVEMENT LCA

Detailed step-by-step instructions for a conducting a complete LCA—but without specifics regarding application to pavement—are presented in an EPA document (SAIC 2006) and in a similar document from the European Environment Agency (Jensen et al. 1997). An initial framework for pavement LCA has been developed (UCPRC 2010a), and a number of studies and symposiums (UCPRC 2010b; IFSTTAR and CSTB 2012) addressing specific pavement LCA issues have been hosted. In addition, case studies using improved LCA models have been performed to address specific questions, such as improving the sustainability of concrete pavements (Santero, Masanat, and Horvath 2011), identifying the net effects of maintaining smooth pavement and the improved fuel economy of vehicles using smoother pavement (Wang et al. 2012), and the reconstruction/rehabilitation of existing freeways (Weiland and Muench 2010). These case studies reflect the application of more standardized practice for pavement LCA and can provide a starting point for developing an approach to use LCA to answer important life cycle environmental questions pertaining to pavements.

Although there are no generally accepted LCA tools for pavements in the U.S., there are a number of commercially available LCA software (for example, Gabi and SimaPro are commercially available databases and tools, and Athena and PE-2 were developed with industry and government funding) that include LCI datasets for pavement that can be used to develop LCA models. The FHWA has not reviewed and does not endorse any LCA or LCI data sets at this time. A number of other tools are being developed in North America, and it can be expected that these will be available within the next several years. These will likely be substantially improved once a standardized framework is developed and resources are committed to addressing the primary sources of lack of consensus previously noted.

APPROACHES FOR IMPLEMENTATION OF LCA "THINKING"

LCA results are currently not utilized for procurement purposes in the design-bid-build (low-bid) project delivery system used in most of North America, although they are being used in some European countries. Another use for LCA is to apply consequential analyses to identify the effects of making changes in a project or policy. The following are some steps that can be taken to begin implementing LCA concepts into the decision-making process:

1. Identify questions to be answered and specific environmental goals to be achieved. In many cases the questions regard the impact of a change in policy or the design of a specific project as compared with current practice (as the base condition).
2. Define system boundaries, including identifying what items are the same across a comparison study so that they need not be considered in the analysis.
3. Define the functional unit and the approach required for sensitivity analyses (specific project variables or a number of cases for evaluating a policy that span the expected ranges of conditions).
4. Identify the types of operations and materials that occur within the system, and how their type and numbers change for the options being considered. (At this point, a comparison of units of something used or consumed may be enough to identify the net effects of the proposed change on the system, particularly if only one type of input or output changes.)
5. Identify appropriate environmental data sets (life cycle inventory data) needed and continue with the life cycle inventory, impact assessment, and interpretation phases of the LCA as described previously.

The completion of the first four phases of this process can often identify whether the rest of the LCA needs to be completed because of the potential complexity of the answer, or whether it is clear that one alternative will have a reduced environmental impact (Harvey et al. 2013).

SUMMARY

Decision making regarding potential changes in pavement practice to improve environmental sustainability is a complex and difficult undertaking. The application of LCA can help define pavement systems to support decision making regarding changes to policies and practices to reduce the impacts of pavements on humans and the environment (and often reduce cost as well), while identifying potential unintended negative consequences. Full LCA requires access to relevant data sets and/or software, which are currently limited and generic; however, it is expected that LCA tools for pavement decision making will emerge in the near future as the understanding of the process improves and data become more available. Furthermore, it is anticipated that over the next several years there will be greater standardization of pavement LCA frameworks and practices, and improvements in LCI data as PCRs and EPDs become more commonplace. Applications of pavement LCA are expected to expand and be used for both policy and practice, and will require further development in the areas of impact assessment and handling of uncertainty.

REFERENCES

Bare, J. 2011. "TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0." *Clean Technologies and Environmental Policy*. Vol. 13, No. 5. Springer. (Web Link)

Environmental Protection Agency (EPA). 2012. *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) User's Manual*. Document ID: S-10637-OP-1-0. U.S. Environmental Protection Agency, Washington, DC.

Environmental Protection Agency (EPA). 2014. *Introduction to Eco-Labels and Standards*. U.S. Environmental Protection Agency, Washington, DC. (Web Link)

European Commission (EC). 2011. *Buying Green! A Handbook on Green Public Procurement*. 2nd Edition. Publications Office of the European Union, Luxembourg. (Web Link).

Georgia Institute of Technology (Georgia Tech). 2010. *AIA Guide to Building Life Cycle Assessment in Practice*. The American Institute of Architects. Washington, DC. (Web Link).

Guinée, J. B. 2012. "Life Cycle Assessment: Past, Present and Future." *International Symposium on Life Cycle Assessment and Construction*. *July 10-12, Nantes, France*. Keynote Address. RILEM Publications, France.

Guinée, J. B., M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. W. Sleeswijk, S. Suh, H. A. Udo de Haes, H. de Bruijn, R. van Duin, and M. A. J. Huijbregts. 2002. *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards.* ISBN 1-4020-0228-9. Kluwer Academic Publishers, Dordrecht.

Harvey, J., A. Kendall, D. Jones, and T. Wang. 2013. "Life Cycle Assessment for Local Government Pavements: What Questions Should We Be Addressing and How?" *Proceedings, ASCE Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements*. Transportation & Development Institute of ASCE, Reston, VA.

Hunt, R. and W. Franklin. 1996. "LCA – How it Came About, Personal Reflections on the Origin and the Development of LCA in the USA." *International Journal of Life Cycle Assessment*. Vol. 1, No. 1. Ecomed Publishers, Landsberg, Germany.

IFSTTAR and CSTB. 2012. *International Symposium on Life Cycle Assessment and Construction. July 20-12, 2012. Nantes, France*. French Institute for Transports, Development and Networks and the French Scientific and Technical Centre of the Building Industry. (Web Link)

International Organization for Standardization (ISO). 2006a. *Environmental Management – Life Cycle Assessment – Principles and Framework*. ISO Standard 14040. International Organization for Standardization, Geneva, Switzerland.

International Organization for Standardization (ISO). 2006b. *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. ISO Standard 14044. International Organization for Standardization, Geneva, Switzerland.

International Organization for Standardization (ISO). 2006c. *Environmental Labels and Declarations -- Type III Environmental Declarations—Principles and Procedures*. ISO Standard 14025. International Organization for Standardization, Geneva, Switzerland.

Jensen, A., L. Hoffman, B. Møller, A. Schmidt, K. Christiansen, S. Berendsen, J. Elkington, and F. van Dijk. 1997. *Life Cycle Assessment (LCA), A Guide to Approaches, Experiences and Information Sources*. Environmental Issues Series No. 6. European Environment Agency. (Web Link).

Kendall, A. 2012. *Life Cycle Assessment for Pavement: Introduction*. Presentation in Minutes, FHWA Sustainable Pavement Technical Working Group Meeting, April 25-26, 2012, Davis, CA.

Mukherjee, A., B. Stawowy, and D. Cass. 2013. "Project Emissions Estimator (PE-2): Tool to Aid Contractors and Agencies in Assessing Greenhouse Gas Emissions of Highway Construction Projects." *Transportation Research Record 2366*. Transportation Research Board, Washington, DC.

Santero, N., A. Loijos, M. Akbarian, and J. Ochsendorf. 2011. *Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle*. Massachusetts Institute of Technology, Cambridge, MA.

Santero, N., E. Masanat and A. Horvath. 2011. "Life Cycle Assessment of Pavements. Part I: Critical Review." *Resources, Conservation and Recycling*. Vol. 55, No. 9–10. Elsevier, Philadelphia, PA. .

Scientific Applications International Corporation (SAIC). 2006. *Life Cycle Assessment: Principles and Practice*. EPA/600/R-06/060. U.S. Environmental Protection Agency, Cincinnati, OH. (Web Link).

University of California Pavement Research Center (UCPRC). 2010a. *Pavement Life Cycle Assessment Workshop: Discussion Summary and Guidelines*. UCPRC-TM-2010-03. University of California Pavement Research Center, Davis, CA. (Web Link)

University of California Pavement Research Center (UCPRC). 2010b. *Pavement Life Cycle Assessment Workshop. University of California, Davis, CA, May 5-7, 2010.* University of California Pavement Research Center, Caltrans, ITS UC Davis, ITS Berkeley, International Society for Asphalt Pavements, and International Society for Concrete Pavements. (Web Link)

Wang, T., I. S. Lee, J. Harvey, A. Kendall, E. B. Lee, and C. Kim. 2012. UCPRC Life Cycle Assessment Methodology and Initial Case Studies for Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance. UCPRC-RR-2012-02. California Department of Transportation, Sacramento, CA.

Weiland, C. D. and S. T. Muench. 2010. *Life Cycle Assessment of Portland Cement Concrete Interstate Highway Rehabilitation and Replacement*. WA-RD 744.4. Washington State Department of Transportation, Olympia, WA. (Web Link)

Contact—For more information, contact:

Federal Highway Administration (FHWA)
Office of Asset Management, Pavements and Construction
Gina Ahlstrom (Gina.Ahlstrom@dot.gov)

Researcher—This TechBrief was developed by John Harvey (University of California, Davis), Joep Meijer (theRightenvironment, Inc.), and Alissa Kendall (University of California, Davis) and prepared under FHWA's Sustainable Pavements Program (DTFH61-10-D-00042). Applied Pavement Technology, Inc. of Urbana, Illinois served as the contractor to FHWA.

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