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Pavement Life Cycle Assessment Workshop: Discussion Summary and Guidelines

Prepared by the UCPRC Pavement LCA Research Team

J. Harvey, A. Kendall, I.-S. Lee, N. Santero, T. Van Dam, T. Wang

University of California, Davis
Davis, California

Project Sponsors:

Collaborators:

DOCUMENT RETRIEVAL PAGE	**Technical Memorandum: UCPRC-TM-2010-03**

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Author: Prepared by the UCPRC Pavement LCA Research Team: J. Harvey, A. Kendall, I.-S. Lee, N. Santero, T. Van Dam, T. Wang

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Abstract:

Operation of the state and national pavement network, which includes both its construction and maintenance, incurs the use of large amounts of energy and natural resources, and results in the emission of significant quantities of greenhouse gases (GHGs), criteria air pollutants, and water pollutants. As recognition of the harm caused by these substances and the costs of resources has increased, significant efforts are now underway to mitigate them and their environmental impacts. However, as is the case whenever a systemic process is changed to reduce its environmental impact, the possibility exists that policy changes can have unintended negative consequences that can actually cause greater environmental harm. The risk of unintended negative consequences is greatest when changes are made that affect one part of a system or life-cycle phase, but the effects of the changes on the rest of the system and the other life-cycle phases are not evaluated. Life cycle assessment (LCA) is an approach for investigating the consequences of changes that when properly applied considers both systems analysis and the entire life cycle. Although there have been several LCA studies on the subject of pavement, nearly all of them have focused on pavement type selection (asphalt or concrete) for new pavements for a narrow range of conditions, and the results have offered conflicting answers to questions about the resulting environmental impacts. This inconsistency is due to the lack of consistent LCA practice and to use of different data sources. Among the specific recurring problems found in LCA are unrepresentative functional units and analysis periods, a lack of transparency in impact allocation of the bitumen-refining process, and incomplete consideration of the full life cycle. Until these issues are resolved, they will continue to make it difficult to use LCA for pavement-related decision making.

To address these issues for Caltrans and interested collaborators, the University of California Pavement Research Center (UCPRC, Davis and Berkeley) and the University of California Institute of Transportation Studies (Berkeley and Davis) have undertaken work together on recommending common practices for conducting LCA for pavements. The first-stage research product arising from this work intended for pavement LCA practitioners is the *UCPRC Pavement LCA Guideline*, which includes a high-level LCA framework for pavements, as well as some recommended data and models that have been used in California and elsewhere in the U.S. In May 2010, a workshop was held in Davis, California, to discuss the first draft of this guideline, and to answer some key questions regarding LCA practice and the application of the results. This technical memorandum contains a summary of the workshop discussions and the final draft *Guideline* based on the discussions.

Keywords:
Pavement; Life Cycle Assessment; Greenhouse gas; Energy consumption

Proposals for implementation: It is recommended that the guidelines be adopted for use in life cycle assessment studies for pavement-related environmental decision-making.

Related documents:

Signatures

J. Harvey **First Author**	J. Harvey A. Kendall **Technical Review**	D. Spinner **Editor**	J. Harvey A. Kendall **Principal Investigators**	W. Nokes **Caltrans Technical Advisory Panel Tech Lead**	T. Joseph Holland **Caltrans Contract Manager**

DISCLAIMER

The contents of this workshop document reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration, the University of California, the MIRIAM project or its sponsors, the International Society for Concrete Pavements, or the International Society for Asphalt Pavements. This workshop document does not constitute a standard, specification, or regulation.

PROJECT OBJECTIVES

These are the objectives of Partnered Pavement Research Center (PPRC) Strategic Plan Element 4.26, "Studies to Support Global Climate Change Initiative":

- Develop an initial LCA framework, including standard assumptions, system boundaries, and documentation requirements, and review, critique, and modify it with an expert group through a workshop to produce a final version,
- Develop data, methods, and models for use within the final LCA framework for simulation of greenhouse gas emissions and energy use on the state highway network as a function of state pavement management practices,
- Produce initial case studies applying the framework and data, methods, and models, in order to demonstrate their use and to provide a preliminary indication of the net effects (considering the entire life cycle as defined by the framework, including materials production, construction and vehicle use) on greenhouse gas emissions and energy use of changes in pavement smoothness and surface texture from pavement maintenance or rehabilitation.

This technical memorandum completes the first objective. Another report completes the second and third objectives.

ACKNOWLEDGMENTS

The research associated with this paper was conducted as a part of the Partnered Pavement Research Program supported by the California Department of Transportation (Caltrans). This research is funded by the California Department of Transportation in partnership with the MIRIAM (Models for Rolling Resistance in Road Infrastructure Asset Management Systems, *http://miriam-co2.net/)* pooled-fund project, which is led by the Danish Road Institute (Ministry of Transportation, Road Directorate) and UC Multi-campus Research Programs and Initiatives (MRPI). The Principal Investigators are John Harvey and Alissa Kendall. The authors also wish to thank the participants of the workshop for their candid contributions of knowledge, experience, and perspective, and the participants and students who helped organize and run the workshop.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AADT	Average annual daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies (software)
Caltrans	California Department of Transportation
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CRCP	Continuously reinforced concrete pavement
CTB	Cement-treated base
DOT	Department of Transportation
EIO-LCA	Economic input-output life cycle assessment
EOL	End-of-life
EPA	Environmental Protection Agency
ESAL	Equivalent single axle load
FHWA	Federal Highway Administration
GHG	Greenhouse gas
GWP	Global warming potential
HMA	Hot-mix asphalt
HTP	Human toxicity potential
IPCC	Intergovernmental Panel on Climate Change
IRI	International Roughness Index
ISO	International Organization for Standardization
JPCP	Jointed plain concrete pavement
LBNL	Lawrence Berkeley National Laboratory
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LEED	Leadership in Energy and Environmental Design
M&R	Maintenance and rehabilitation
MIRIAM	Models for rolling resistance In Road Infrastructure Asset Management Systems
MPD	Mean profile depth
MTD	Mean texture depth
MSOD	Mobile Source Observation Database
MSWI	Municipal solid waste incineration
N_2O	Nitrous oxide
NO_X	Nitrogen oxides
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
Pb	Lead
PeMS	Performance Measurement System
PCA	Portland Cement Association
PCC	Portland cement concrete
PIARC	World Road Association
PM_{10}	Particulate matter with diameters of 10 microns or smaller
$PM_{2.5}$	Particulate matter with diameters of 2.5 microns or smaller

PMS	Pavement Management System
RAP	Recycled asphalt pavement
RCP	Recycled concrete pavement
RHMA	Rubberized hot-mixed asphalt
SETAC	Society of Environmental Toxicology and Chemistry
SO_2	Sulfur dioxide
SO_X	Sulfur oxides
UCPRC	University of California Pavement Research Center
VKT	Vehicle kilometers traveled
VMT	Vehicle mileage traveled
VOC	Volatile organic compound
WMA	Warm-mix asphalt

GLOSSARY[*†]

Abiotic resource. An *abiotic resource* is one that comes from a non-living source, such as land, water, air, or minerals.

Analysis period. The *analysis period* is the time horizon during which the inputs and outputs associated with the functional unit for a system or systems are inventoried.

Allocation. *Allocation* is the partitioning of the input or output flows of a *process* or a *product system* between the product system under study and one or more other product systems. *(1)*

Attributional Life Cycle Analysis and Consequential Life Cycle Analysis. An *attributional life cycle analysis (LCA)* is defined as an attempt to answer "How are things (i.e., pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?" while a *consequential LCA* attempts to answer "How will flows beyond the immediate system change in response to decisions?" For example, an attributional LCA would examine the consequences of using green power compared to conventional sources. A consequential LCA would consider the consequences of this choice in that only a certain amount of green power may be available to customers, causing some customers to buy conventional energy once the supply of greener sources was gone. The choice between conducting an attributional or a consequential assessment depends on the stated goal of the study. *(4)*

Bitumen upgrading. *Bitumen upgrading* is the conversion of bitumen into lighter fractions with better combustion-related properties than those associated with the direct combustion of bitumen as a fuel.

Bottleneck. A *bottleneck* is a road element in which demand exceeds capacity. *(3)*

CO_2-equivalent (CO_2-e). *CO_2-equivalent* is the amount of CO_2 emission that would cause the same time-integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived *GHG* or a mixture of GHGs. Because GHGs differ in their warming influence (radiative forcing) on the global climate system due to their different radiative properties and lifetimes in the atmosphere, these warming influences may be expressed through a common metric based on the radiative forcing of CO_2. Therefore the CO_2-equivalent is obtained by multiplying the emission of a GHG by its *global warming potential (GWP)* for the given time horizon. For a mix of GHGs it is obtained by summing the equivalent CO_2 of each gas. Equivalent CO_2 is a standard and useful metric for comparing emissions of different GHGs but does not imply the same climate change responses. *(2)*

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[*] For entries containing a citation, text is either quoted or condensed from the item listed in the Glossary Sources section that appears on page xv.

[†] Terms included in the Glossary have been set in italic in their first appearance within the memo.

CO_2 sequestration (Uptake of carbon). *CO_2 sequestration* (or *uptake of carbon)* is the addition of carbon dioxide to a reservoir. *(2)*

Co-product. A *co-product* is any of two or more products coming from the same *unit process* or *product system. (1)*

Coking. *Coking* is an oil refinery process that converts the residual oil from a vacuum distillation column or an atmospheric distillation column into low molecular weight hydrocarbon gases, naphtha, light and heavy gas oils, and petroleum coke. The process thermally cracks the long chain hydrocarbon molecules in the residual oil feed into shorter chain molecules. There are three coking methods used in oil refineries: delayed coking, fluid coking, and Flexicoking™.

Congested traffic flow. *Congested traffic* is a traffic flow condition caused by a downstream *bottleneck. (3)*

Construction traffic flow. Construction activities on a freeway can lead to capacity reductions; *construction traffic flow* is the traffic flow affected by this reduced capacity. *(3)*

Cut-off criteria. *Cut-off criteria* are the specifications of the amount of material or *energy flow,* or the level of environmental significance associated with the *unit processes* or *product system* to be excluded from a study. *(1)*

Data quality. *Data quality* is the characteristic of data that relates to its ability to satisfy stated requirements. *(1)*

Down-cycling. *Down-cycling* is the process of recycling used materials or products into new materials or products of lesser quality and reduced functionality.

Elementary flow. *Elementary flow* is the material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation. *(1)*

Energy flow. *Energy flow* is the input to or output from a *unit process* or *product system,* quantified in energy units. *(1)*

Feedstock energy. *Feedstock energy* is the 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. *(1)*

Functional unit. A *functional unit* is the quantified performance of a *product system* for use as a reference unit. *(1)*

Global warming potential (GWP). *Global warming potential* is an index based upon the radiative properties of well-mixed *greenhouse gases,* measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in today’s atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. The Kyoto Protocol is based on GWPs from pulse emissions over a 100-year time frame. *(2)*

Green construction (Green building). *Green construction* (or *green building)* is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle, which includes siting, design, construction, operation, maintenance, renovation and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Green buildings are designed to reduce the overall impact of the built environment on human health and the natural environment by: (1) efficiently using energy, water, and other resources, (2) protecting occupant health and improving employee productivity, and (3) reducing waste, pollution, and environmental degradation. *(6)*

Greenhouse gases (GHGs). *Greenhouse gases* are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary *greenhouse gases* in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). *(2)*

Impact category. An *impact category* is a class of environmental impacts that represent environmental issues of concern, and to which *life cycle inventory analysis* results may be assigned. *(1)*

Impact category indicator. An *impact category indicator* is a quantifiable representation of an *impact category*. For example, *global warming potential* is the impact category indicator of the impact category "climate change."

International Organization for Standardization (ISO). The *ISO* is an international standards-setting body composed of representatives from a variety of national standards organizations.

ISO 12006-3:2007. The standard *ISO 12006-3:2007* is an international one used for organizing information about construction works. Part 2 of this standard gives the framework for classification of information.

ISO 14040:2006. The standard *ISO 14040:2006* describes the principles and framework for *life cycle assessment (LCA)* including: definition of the goal and scope of the LCA, the *life cycle inventory analysis (LCI)* phase, the *life cycle impact assessment (LCIA)* phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. The standard covers LCA studies and LCI studies, but it neither describes the LCA technique in detail nor specifies methodologies for individual phases of an LCA. The intended application of LCA or LCI results is considered during definition of the goal and scope, but the application itself is outside the scope of this International Standard.

ISO 14044:2006. The standard *ISO 14044:2006* specifies requirements and provides guidelines for life cycle assessment (LCA), including the definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements.

Leadership in Energy and Environmental Design (LEED). *LEED* is a green building certification system developed by the U.S. Green Building Council. It is intended to provide third-party verification that a building or community was designed and built using strategies intended to improve performance in metrics such as energy savings, water efficiency, CO_2-emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts. *(7)*

Life cycle. A *life cycle* is the consecutive and interlinked stages of a *product system,* from raw material acquisition or generation from natural resources to final disposal. *(1)*

Life cycle cost analysis (LCCA). In transportation engineering, *LCCA* is an engineering economic analysis tool that allows transportation officials to quantify the differential costs of alternative investment options for a given project. LCCA can be used to study new construction projects and to examine preservation strategies for existing transportation assets. LCCA considers all agency expenditures and user costs throughout the life of an alternative, not only initial investments. More than a simple cost comparison, LCCA offers sophisticated methods to determine and demonstrate the economic merits of the selected alternative in an analytical and fact-based manner. LCCA differs from LCA in that current LCCA doesn't include the cost from the damage to the environment in the analysis system, and their targets (economic cost and environment) have completely different characterization methods. *(5)*

Life cycle assessment (LCA). *LCA* is a compilation and evaluation of the inputs, outputs, and potential environmental impacts of a *product system* throughout its life cycle. *(1)*

Life cycle impact assessment (LCIA). *LCIA* is a phase of *life cycle assessment* aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a *product system* throughout the life cycle of a product. *(1)*

Life cycle inventory (LCI). *LCI* is the phase of *life cycle assessment* involving the compilation and quantification of inputs and outputs for a product throughout its life cycle *(1)*. An LCI can also be conducted separately, without being part of an LCA study.

Models for rolling resistance In Road Infrastructure Asset Management Systems (MIRIAM). *MIRIAM* is a project started by twelve partners from Europe and the U.S. that aims to provide information useful for achieving a sustainable and environmentally friendly road infrastructure. The project's focus is on reducing the energy consumption due to tire/road interaction by identifying pavements that have lower rolling resistance and which, if used, would lower CO_2 emissions and increase energy efficiency.

Multiple-criteria decision making. *Multiple-criteria decision making* is a subdiscipline of operations research that explicitly makes a choice among options involving multiple, and often conflicting, criteria. In the pavement field, typical multiple conflicting criteria include cost, structural performance, and environmental benefit. It is unusual to construct the cheapest pavement with the best structural performance and greatest environmental benefit.

Non-renewable resource. A *non-renewable resource* is a natural resource that cannot be produced, grown, generated, or used on a scale that can sustain its consumption rate, and once this resource type is depleted it becomes unavailable for the future. Resources that are consumed much faster than nature can create them are also considered to be non-renewable.

Normal traffic flow. *Normal traffic flow,* as used in this document, is defined as traffic flow without a construction event.

Off-road equipment. *Off-road equipment*, as used in this document, is defined as the construction equipment used on a construction site and not that traveling on roadways.

Pareto Frontier. The *Pareto frontier* is the set of choices that reach *Pareto optimality,* given a set of choices and a way of valuing them.

Pareto optimality (Pareto efficiency). *Pareto optimality,* or *Pareto efficiency,* is a condition where an allocation of resources among a set of individuals cannot be redistributed in a way that makes it possible for one individual to benefit without another one becoming worse off.

Primary energy. *Primary energy* comes from energy sources found in their natural state, as opposed to derived or *secondary energy*.

Process. A *process* is a set of interrelated or interacting activities that transforms inputs into outputs. *(1)*

Process energy. *Process energy* is the energy input required for operating the process or equipment within a *unit process,* excluding energy inputs for production and delivery of the energy itself. *(1)*

Product flow. *Product flow* refers to the product or products entering from or leaving for another product system. *(1)*

Product system. A *product system* is a collection of unit processes with *elementary* and *product flows*, performing one or more defined functions, and which models the *life cycle* of a product. *(1)*

Radiative forcing. *Radiative forcing* is the change in the net, downward minus upward, irradiance (expressed in Watts per square meter, W/m^2) at the tropopause due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the sun. Radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called "instantaneous" if no change in stratospheric temperature is accounted for. For the purposes of this document, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value. *(2)*

Scenario analysis. *Scenario analysis* is the analysis of a plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios, which are sometimes combined with a narrative story line, may be derived from projections but are often based on additional information from other sources. *(2)*

Secondary energy (derived energy). *Secondary energy*, or *derived energy*, is the result of the transformation of primary or secondary energy sources.

Sensitivity analysis. A *sensitivity analysis* is comprised of systematic procedures for estimating the effects of choices made regarding methods and data on the outcome of a study. *(1)*

Stormwater runoff. *Stormwater runoff* is generated when precipitation from rain and snowmelt events flows over land or impervious surfaces (such as paved streets, parking lots, and building rooftops) without percolating into the ground. As this runoff flows, it can accumulate debris, chemicals, sediment, and other pollutants that might adversely affect water quality if the flow is discharged untreated. *(6)*

System boundary. A *system boundary* is the set of criteria specifying which unit processes are part of a *product system. (1)*

Transparency. *Transparency* is the open, comprehensive, and understandable presentation of information. *(1)*

Uncertainty analysis. An *uncertainty analysis* is a systematic procedure for quantifying the uncertainty introduced into the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty, and data variability. *(1)*

Unit process. A *unit process* is smallest element considered in the *life cycle inventory analysis* for which input and output data are quantified. *(1)*

Glossary Sources

1. International Organization for Standardization. *ISO 14040 Environmental management—Life cycle assessment—Principles and framework*. ISO 14040:2006(E). International Organization for Standardization, Geneva, 2006.
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6. U.S. Environmental Protection Agency. Green Building: Basic Information. *www.epa.gov/greenbuilding/pubs/about.htm* (Accessed Sep. 2011).
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SECTION I: BACKGROUND

It is estimated that about $160 billion and 320 million metric tons of raw materials are used annually in construction and maintenance activities related to the U.S. highway system, a fundamental component of the transportation infrastructure that is critical to the national economy. Operating this national pavement network incurs the use of enormous amounts of energy and results in the emission of significant quantities of *greenhouse gases* (GHGs), criteria air pollutants, and water pollutants. As the costs and the harm caused by these pollutants have become more widely recognized, significant efforts have been undertaken to mitigate them and their environmental impacts.

However, as is the case whenever a systemic process is changed to reduce its environmental impact, there is the possibility that policy changes can have unintended negative consequences that can actually cause greater environmental harm. The risk of unintended negative consequences is greatest when changes are made that affect one part of a system or life-cycle phase, but the effects of the changes on the rest of the system and the other life-cycle phases are not evaluated. *Life cycle assessment* (LCA) is an approach for investigating the consequences of changes that when properly applied considers *systems analysis* and the entire life cycle.

The value of LCA is that it provides a comprehensive approach to evaluating the total environmental burden of a product, examining it from cradle-to-grave—that is, this approach evaluates all the inputs and outputs, from raw material production to the end-of-life. For pavement, this cycle includes the material production, construction, use, maintenance and rehabilitation (M&R), and end-of-life (EOL) phases.

Currently, pavement LCA practitioners lack a well-tested method or comprehensive body of knowledge for performing these assessments, and this document is part of an effort to provide some coherence to the development of a practice. Although the *International Organization for Standardization (ISO)* has set up a series of standards for conducting LCA on products (ISO 14040 series) *(1)*, performing an LCA on pavement is much more complex than it is for general consumer products *(2, 3)*. In addition, although there have been several LCA studies on the subject of pavements, nearly all of them have focused on pavement type selection (asphalt or concrete) for new pavements for a narrow range of conditions, and the results have offered conflicting answers to questions about the resulting environmental impacts. These question addressed by these studies ignores the fact that most road-owning agencies in the developed world are primarily concerned with the maintenance and rehabilitation of existing road networks, not construction of new pavement.

Among the specific recurrent problems found in pavement LCA studies to date are unrepresentative *functional units* and *analysis periods,* a lack of *transparency* in the impact *allocation* of the bitumen-refining process, and incomplete scope (missing life cycle phases, most typically the Use Phase), lack of state-of-the-art models for many sub-processes in the pavement life cycle, and lack of impact allocation at the EOL phase. In addition, many studies have relied on a single data source, while in reality there may be a range of data for a given process reflecting differences between materials sources, manufacturing processes, transport distances, construction practices, pavement structure and materials design practices, vehicle fleets, and a host of other variables that vary between projects, regions, and over time *(4, 5)*. Until these issues are resolved, they will continue to make it difficult to apply LCA to pavement-related decision making.

This document is one result of a pair of partnerships among academia and government, with additional input coming from industry, to address these problems. One of these partnerships is between the University of California Pavement Research Center (UCPRC, Davis and Berkeley) and the University of California Institute of Transportation Studies (ITS, Berkeley and Davis), which are working together on recommending common practices for conducting environmental LCA for pavements, with partial funding from the California Department of Transportation (Caltrans). In a second collaboration, Caltrans has partnered with the MIRIAM (Models for Rolling Resistance in Road Infrastructure Asset Management Systems, *http://miriam-co2.net/)* Project, which is led by the Danish Road Institute (Ministry of Transportation, Road Directorate). Industry input for that project is coming through collaboration with the International Society for Asphalt Pavements (Asphalt Pavement and the Environment Technical Committee, ISAP APE) and the International Society for Concrete Pavement (ISCP). Further industry insight has been obtained through interaction with the American Concrete Pavement Association (ACPA) and the Asphalt Pavement Association of California (APACA).

Funding for the UCPRC and UC ITS collaboration has come from both the California Department of Transportation (Caltrans) and the University of California (UC). The UC-funded research will extend the results of this work to local transportation networks. The Caltrans-funded work has focused on the State of California highway network, and is considered to be part of the Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.26. These are the objectives of PPRC Strategic Plan Element 4.26, “Studies to Support Global Climate Change Initiative”:

- Develop an initial LCA framework, including standard assumptions, system boundaries, and documentation requirements, and review, critique, and modify it with an expert group through a workshop to produce a final version,
- Develop data, methods, and models for use within the final LCA framework for simulation of greenhouse gas emissions and energy use on the state highway network as a function of state pavement management practices,
- Produce initial case studies applying the framework and data, methods, and models, in order to demonstrate their use and to provide a preliminary indication of the net effects (considering the entire life cycle as defined by the framework, including materials production, construction and vehicle use) on greenhouse gas emissions and energy use of changes in pavement smoothness and surface texture from pavement maintenance or rehabilitation.

This technical memorandum completes the first objective. Another report completes the second and third objectives.

The UCPRC Pavement LCA Research Team (Harvey, Kendall, Lee, Santero, Van Dam, and Wang) and their project's sponsors have compiled this technical memorandum with the following objectives:

- To inform and promote understanding of LCA among pavement LCA practitioners, researchers, pavement engineers, and users of pavement LCA information;
- To encourage decision makers to consider LCA concepts in formulating policies regarding pavements;
- To provide recommendations that pavement LCA practitioners can follow to improve pavement LCA studies and provide greater transparency in documenting them; and
- To provide assumptions, system boundaries, models, and the best available data to pavement LCA practitioners involved in studies in California and in the MIRIAM project, which is a collaboration of Caltrans and international research partners.

This technical memorandum is divided into three sections. This first section provides the background and motivations for the development of pavement LCA guidelines and the workshop that reviewed them. Section II (which begins on page 5), is the *UCPRC Pavement LCA Guideline.* Intended for pavement LCA practitioners, it contains a first-stage research product that arose from the work performed by the collaborators noted above. The *Guideline* includes three parts:

- Part 1, the LCA Framework and Standard Assumptions, contains a high-level LCA framework for pavements and a summary of system boundaries and assumptions for them. The discussion also includes an examination of the pros and cons of some alternatives.
- Part 2, Recommended Models and Data Sources, includes the assessment of models/data for each phase of the life cycle with regard to the level of the LCA study (that is, network-level or project-level).
- Part 3, the Pavement LCA Checklist, is a recommended document for pavement LCA studies. It is a detailed listing of items (such as data sources, uncertainty, transparency, etc.) that will make it possible for pavement LCA practitioners to compare studies in terms of their completeness, assumptions, system boundaries, and data/models.

Section III of this document contains a summary of discussions held among 45 participants (see the Appendix for the list of participants and organizers) from industry, academia, and government at a May 2010 workshop in Davis, California, to discuss the first draft of the *Guideline,* and to answer some key questions regarding LCA practice and the application of LCA results. *It should be noted that the version of the* UCPRC Pavement LCA Guideline *included in this memorandum incorporates the content of many of the comments compiled in the workshop discussions.* The section summarizes workshop activities that included the following:

1. Review and discussion of the three parts of the *UCPRC Pavement LCA Guideline,*
2. Brief descriptions and discussions of the critical issues for pavement LCA, as well as lists of conflicting practices and/or gaps in knowledge that were identified,

3. A summary of areas of consensus and disagreement with regard to the three parts of Section II, as well as documentation of alternative views. (Note: This technical memorandum contains a condensed version of the discussion breakout sessions.)

As noted, this version of the *UCPRC Pavement LCA Guideline* focuses on studies to be performed first by the UCPRC for Caltrans in California and subsequently by the other MIRIAM LCA sub-project participants (VTI in Sweden and ZAG in Slovenia) after their incorporation of European considerations. However, the *Guideline* may also serve as a guide for pavement LCAs performed in any region. A follow up, which is likely to be part of the MIRIAM project, will likely be required to capture similar information for studies focusing on European countries. To that end, the latest version of this *Guideline* has been posted for comment and critique by the pavement and LCA communities.

SECTION II: UCPRC PAVEMENT LCA GUIDELINE
PART 1: LCA FRAMEWORK AND STANDARD ASSUMPTIONS

The *LCA Framework and Standard Assumptions* presented here is intended (1) to provide preliminary definitions for the basic elements of pavement life cycle assessment (LCA), and (2) to provide recommendations for the conduct of pavement LCA studies. The document attempts to address all the processes involved in a pavement *product system* (except the design period) that might impact the environment, with the product defined as a pavement maintenance or rehabilitation treatment. This framework can serve as a guideline either for a comprehensive pavement LCA, such as a study to identify the total impacts over a 40-year life cycle from reconstruction of an asphalt concrete pavement, or a comparative LCA study where only the differing parts of two or more pavement systems are compared. For example, a study that compares warm-mix asphalt and conventional hot-mix asphalt might only include the materials production and construction processes, and assume that the systems perform identically in every other way.

Before discussing pavement LCA in detail, it is important to establish the difference between it and a *roadway LCA.* This delineation between the LCA types is crucial in order to correctly identify what should and should not be included within a pavement LCA. Specifically, the decision to build a roadway is complex one that requires taking into consideration mobility and accessibility issues, as well as other demands. Any decision to proceed with roadway work must also balance a host of social, economic, and environmental issues within the decision-making framework *(6)*. From an environmental impact perspective, construction of a new roadway (or expansion of an existing one) will open up new areas of potential impact, such as those from changes to the local and regional economies associated with the transformed transportation corridor. When performing a roadway LCA, it is critical that these indirect (yet highly influential) issues be accounted for in the procedures and results.

Performing a pavement LCA is more straightforward than performing a roadway LCA, as the former is a subset of the latter. Assuming a reasonable pavement serviceability threshold, accessibility and mobility—two components of a roadway LCA—are indifferent to the type of pavement used, and thus they can be omitted from the pavement LCA scope. This confines the scope of the pavement LCA to issues related to the design, materials, construction, and characteristics of the pavement itself. Isolating pavements from roadways allows for a more focused analysis and encourages recommendations specific to pavements and to their characteristics.

The research team has elected to follow the ISO 14040:2006 protocol, which provides a generic structure and format for LCA for all industrial products, because it is used world-wide for most industries and is the general reference for most LCA discussions for pavements by academia and industry. It has been developed over time through an international critical peer review process, and is subject to periodic review and amendment through that process. Any LCA approach that does not follow the ISO standard, or at least address reasons why certain elements of it are not included, would be considered incomplete when subjected to scientific peer review. The development of a new standard for pavement LCA that does not follow the ISO standard would be outside the mainstream of LCA practice in the U.S. and the rest of the world. In addition to these benefits of following the ISO standard, there is no apparent reason not to follow it.

Based on *ISO 14040:2006*, the following stages should be followed for conducting an LCA, as shown in Figure 1:

1. *Goal and Scope*

   In this first stage, the LCA practitioner should identify the purpose of the LCA practice and define the system boundaries and *functional unit* used for the product.

2. *Life Cycle Inventory*

   This stage involves data collection, and modeling of the product. This includes all the inputs and outputs related to the product and its environment, within the system boundaries and based on the functional unit defined in Goal and Scope. Examples of inventory items include *primary energy consumption, resource consumption, waste flows, air emissions,* and *water pollutants* caused by the product over its life cycle.

3. *Impact Assessment*

   The Impact Assessment stage provides additional information to help assess the product's inventory results. The first step in this stage is to assign the appropriate inventory results to the selected Impact Categories, such as *global warming, ozone depletion,* etc. Then, results that fall into the same category will be characterized and calculated in a category indicator, such as *global warming potential, ozone depletion potential,* etc. The final step is *valuation,* which integrates across impact categories using weights or other approaches, thus enabling decision-makers to assimilate and consider the full range of relevant outcomes. This step provides a basis for comparing different types of environmental impact, taking into account the relative importance of different impact categories. However, because this last step contains very high uncertainty and variability, whereas the second step is usually based on scientifically reliable research, many studies stop at the earlier one, considering it to be a "midpoint" assessment.

4. *Interpretation*

   The Interpretation stage is an analysis from which conclusions are drawn and recommendations are made, or that is used to otherwise inform the decision-making process. Usually, a *sensitivity analysis* and an *uncertainty analysis* are included to confirm any conclusions. Although most studies do not include this review process, as required in ISO 14040:2006, an independent critical review is necessary at this stage, especially for comparisons that will be available in the public domain.

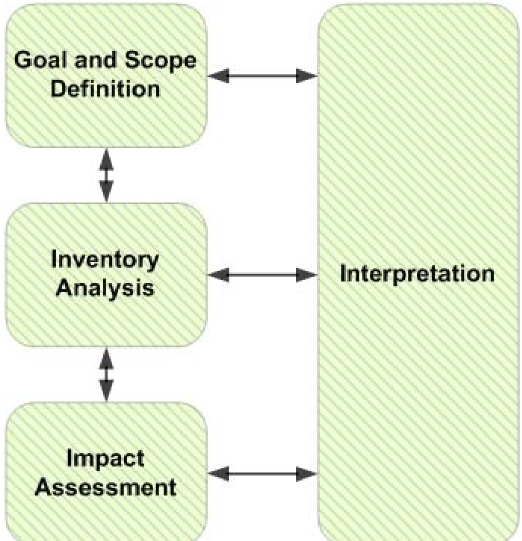


Figure 1: Stages for life cycle assessment (ISO, 2006, pp8)

This *Guideline* follows the steps prescribed in ISO 14040:2006. The items labeled as "elements to be included" in the material that follows are considered significant, and are likely to be included within an LCA's *system boundary* or in a sensitivity analysis. These include:

- Goal and Scope Definition
- Functional Unit
- Analysis Period
- Life Cycle Inventory
- Life Cycle Phases and Their System Boundaries
- Impact Assessment
- Analysis of Uncertainty

Elements considered potentially trivial or in need of further discussion before they are included in the analyses are labeled "elements requiring discussion before deciding on inclusion."

1 Goal and Scope Definition

ISO 14040:2006 requires that a study's goal be defined at the outset of an LCA (*1*). Defining the goal of a pavement LCA includes identifying its purpose and its audience. Among the purposes of performing a pavement LCA are the following:

- To generate information for decision making for a specific project, i.e., for a project-level study, which is work that would be done by or for a project designer or planner who is comparing alternative strategies for treatment of a pavement;
- To characterize a set of discrete projects and their sensitivity to a range of conditions in order to sufficiently inform asset managers about the implications of their decisions and policy choices; this is work that would be performed by or for pavement management staff in order to answer questions posed

to the pavement management unit internally or by external stakeholders regarding subsets within the pavement network; or

- To characterize a complete highway network, i.e., a comprehensive pavement network-level study, which is work that would be performed to help answer policy questions posed by internal or external stakeholders regarding pavement management goals or to determine the effects of proposed changes in policy applicable to the entire network.

The LCA framework provided here is intended to guide a project-level study, not a comprehensive pavement network LCA, meaning it applies to the first two bullet items listed above. In a project-level LCA, site-specific and project-specific information should be used (when available).

Project-level LCAs can serve as a foundation for the analysis of a set of different projects. A project-level LCA may consider network effects, such as the effect on a network from work zone traffic. Conversely, if the goal of the LCA is a framework that can be used across multiple projects, information regarding temporal and spatial variability will need to be addressed. The spatial resolution of a study will be particularly important at the Impact Assessment stage (whether it is a local impact like acid rain or a global impact like global warming) and should be considered if data and models are available.

The goal must also clearly define whether the LCA study intends to quantify the total environmental impacts of one system or to compare several alternative systems. In the former, all the processes that have been identified in a pavement system need to be included within the system boundary. The latter situation allows the reasonable elimination of some components that are identical among systems, thus reducing the study's complexity. The components that are assumed to be the same and are omitted must be explicitly and clearly stated in the study's documentation.

2 Functional Unit

ISO 14040:2006 *(1)* defines a *functional unit* as the "quantified performance of a *product system* for use as a reference unit" (p. 4). For a pavement LCA, the functional unit needs to address both the physical dimension and the pavement performance of the system.

2.1 Physical dimensions

2.1.1 Physical dimensions of pavements refer to length, width, and number of lanes for a highway system. However, for some applications such as parking lots or intersections, total area or other measurements may be more appropriate. Physical dimensions need to reflect the scale of a real-world project because certain activities can only be modeled at the scale of a practical project (e.g., mobilization of equipment or traffic analysis). For highway systems, typical project length could be between 0.5 km and 100 km.

2.1.2 Inclusion of shoulder and median.

2.2 Performance requirement

The main purpose of pavements is to carry traffic safely and efficiently. There are several attributes that define the performance of a pavement in relation to its primary purpose.

2.2.1 Functional design life: the period of time that a newly constructed or rehabilitated pavement is engineered to perform before reaching terminal serviceability or a condition that requires pavement rehabilitation and/or reconstruction *(7)* (Topic 612);

2.2.2 Criteria for performance: functional criteria, such as ride quality and safety, allowed traffic with defined axle load spectrum and speed characteristics, or allowed climate (temperature and rainfall) and/or related engineering criteria, such as structural capacity and level of distress.

3 Analysis Period

The *analysis period* refers to the time horizon during which the inputs and outputs associated with the functional unit for a system or systems are inventoried. The initial construction of each system may have a different functional design life, and may be followed by a series of different maintenance and rehabilitation (M&R) activities to preserve its function. Assessing the pavement system over a time horizon presents a major challenge. Some proposed approaches for determining the analysis period include:

1. Use 1.2 to 1.5 times the longest functional design life among all alternatives; this is the approach used for most Life Cycle Cost Analysis [LCCA] *(8)* where the effect of the current treatment on the next treatment is considered very important (also a consideration for LCA);
2. Use the duration to the next major rehabilitation; and
3. Annualize/amortize construction and M&R events.

4 Life Cycle Inventory

Depending on the goal of an LCA study and the specific environmental impacts to be assessed, the environmental inputs and outputs to be inventoried may vary. However, tracking the life cycle inventory (LCI) of all the available inputs and outputs is recommended to provide information for future use. The recommended inventory items to be tracked include the following:

4.1 Energy consumption, including the *primary energy* and *secondary energy.*

- Note: *Feedstock energy* must be distinguished from combusted energy.

4.2 Greenhouse gas emissions

- This requires the life cycle inventory of major *greenhouse gas* emissions, including CO_2, CH_4, and N_2O. In addition, NO_X, particulates (including black carbon), and other pollutants that are emerging as significant climate change factors should also be included as the scientific consensus develops on their effects and global warming potentials.

4.3 Material flows, including fossil*/non-renewable resource* flows and water flow.

4.4 Air pollutants, including NO_X, Volatile Organic Compounds (VOCs), PM_{10}, $PM_{2.5}$, SO_2, CO, and lead.

- Emissions from potential use of bitumen-based fuel should be considered if the type of LCA approach is *consequential*. It should not be considered if the LCA is *attributional*.

4.5 Water pollutants and solid waste flows, including toxics or hazardous waste.

5 Life Cycle Phases and Their System Boundaries

The life cycle phases of a pavement system include material production, construction, use, maintenance and rehabilitation, and end-of-life. A framework that includes each phase and some sample materials/processes is shown on page 16. It should be noted that a pavement LCA needs to consider the structural design of each alternative including surface, base, subgrade, shoulder, and drainage. If the LCA is applied to a preservation, maintenance, or rehabilitation activity where the base/subgrade/drainage remains unchanged, these aspects of the structural design can be left outside the system boundary.

5.1 Material Production Phase

The Material Production Phase of a pavement LCA includes the raw material acquisition (from natural resources) and transport to the mixing plant. Such materials include but are not limited to bitumen, cement, aggregate, sand, etc.

5.1.1 Elements to be included:

5.1.1.1 Material acquisition/production

5.1.1.2 Mixing processes of asphalt concrete or cement concrete in plants

5.1.1.3 Feedstock energy of materials that are used as a fuel

5.1.1.4 Transport of materials from/to site, and from/to mixing plant

5.1.2 Elements requiring discussion before deciding on inclusion:

5.1.2.1 Cut-off rule for oil excavation and refining

5.1.2.2 Allocation of impacts during oil refining (asphalt production)

5.1.2.3 Technology related to material production, such as bitumen refining or aggregate production improvement over time

5.1.2.4 Equipment manufacturing and capital investments in production facilities

5.1.3 Elements outside the system boundary:

5.1.3.1 Land use/occupancy

5.2 Construction Phase and Maintenance and Rehabilitation Phase

Because M&R is essentially a construction event, its system boundary should be consistent with the construction phase. The system boundary of the Construction and M&R phases includes the construction equipment usage and the affected traffic flow.

5.2.1 Elements to be included:

5.2.1.1 Transport of materials and equipment to site

5.2.1.2 Equipment manufacturing and capital investments solely attributable to this construction event

5.2.1.3 Equipment use at the site

5.2.1.4 Water transport

5.2.1.5 Water use during construction

5.2.1.6 Energy and emissions used for lighting, if construction occurs at night

5.2.1.7 Storm water system (drainage): generally included. For a specific project, if an alternative design changes the drainage then it should be included, otherwise it can be excluded.

5.2.1.8 Emissions/fuel consumption due to traffic congestion during construction

- Changes to traffic flow during construction events should be included in the analysis.
- Critical changes to traffic over time should be included in a sensitivity analysis or a similar assessment.
  - Fleet composition
  - Speed distribution
  - Traffic growth change
  - Improvement of vehicle technology and emissions standards

5.2.1.9 Building of roadway lighting system

5.2.1.10 Temporary infrastructure

5.2.2 Elements outside the system boundary:

5.2.2.1 Equipment manufacturing and capital investments for recurring construction events

5.3 Use Phase

The Use Phase of a pavement accounts for impacts incurred due to its use. These impacts include additional fuel for vehicle operation due to the deterioration of the pavement (including added fuel consumption, damage to vehicles, damage to freight, and tire wear), the heat island effect from the pavement, the non-GHG climate change effect from pavement albedo, the roadway lighting effect due to pavement albedo, the carbonation of concrete pavement, and water pollution from leachate and runoff.

5.3.1 Elements to be included:

5.3.1.1 Additional consumption by vehicles due to pavement deterioration

Impacts from additional vehicle operation due to pavement deterioration include the effect on fuel economy, damage to vehicles, damage to freight, and tire wear. Traffic growth, fleet composition, speed distribution, and vehicle technology improvement should be included in a sensitivity analysis.

5.3.1.2 Heat island effect

The mechanisms that affect the heat island effect include albedo and evaporative cooling (for pervious pavement). The heat island effect causes changes in the energy consumption associated with the heating/cooling of buildings or vehicles, and degrades the quality of water runoff. Because this is a location-specific concern, pavement temperature and reflectance need to be included in a sensitivity analysis, and their effects must be explicitly defined in the study's documentation.

5.3.1.3 Non-GHG climate change effect

At present, only the *radiative forcing* from albedo is considered. Radiative forcing can be interpreted as the rate of energy change per unit area of the globe as measured at the top of the troposphere due to external factors. High albedo contributes to global cooling by reflecting a portion of the incoming radiation back to space, thus producing a negative radiative forcing. This impact can be quantified by calculating reduced radiative forcing and then converting it to CO_2-e.

5.3.1.4 Roadway lighting

This generally includes electricity use.

5.3.1.5 Carbonation

Carbonation occurs when the components of cement, such as $Ca(OH)_2$, react with CO_2, and sequester it in the pavement.

5.3.1.6 Water pollution from leachate and runoff

5.3.2 Elements requiring discussion before deciding on inclusion:

5.3.2.1 Long-term emissions of GHGs and other pollutants from asphalt due to asphalt binder-aging chemistry

5.3.2.2 Reduced fuel efficiency and increased emissions due to differences in rolling resistance based on pavement type (asphalt/concrete/composite). Although existing research suggests that pavement type plays a factor in rolling resistance, it is unclear if the information available is sufficient to warrant quantitative inclusion in an LCA.

5.4 End-of-Life Phase (Material Recycling and Landfilling)

The End-of-Life Phase of pavement accounts for the impacts from handling debris after the pavement's functional life ends. Two ways to deal with pavement after it reaches its end of life include recycling and landfilling.

5.4.1 Elements to be included:

5.4.1.1 Recycling imposes a critical problem regarding the allocation of net input/output between the system that generates the "waste" and the one that recycles it. The method of input/output allocation and the crediting of virgin material savings resulting from use of recycled materials need to be justified and documented in an LCA study.

5.4.1.2 Emissions and fuel use from demolition and hauling of debris

5.4.2 Elements requiring discussion before deciding on inclusion:

5.4.2.1 Leachate from landfilling

5.4.2.2 Leachate from formerly bound materials now being used as unbound base

6 Impact Assessment

Impact Assessment translates the inventory into meaningful indicators of a product's or system's impact on the environment and human health. In most LCA studies, this is achieved by classifying inventory flows into impact categories and characterizing the inventory results through the *impact category indicators.* For example, by using *CO_2-equivalent,* the impact from all greenhouse gases are calculated and combined into the impact category *global warming.* Impact categories include but are not limited to the following:

6.1 Global warming (or climate change)

The inventory of greenhouse gases should be tracked and reported in CO_2-equivalents or a similarly well-understood climate change indicator. The analysis must report the method used to calculate CO_2-equivalents and the method's source.

6.2 Resource depletion

This translates the inventory of material flows into categories of consumption, such as non-renewable use or *abiotic resource* use.

6.3 Other impact categories, such as human toxicity, ecotoxicity, ozone depletion, or acidification.

7 Analysis of Uncertainty

Like other infrastructure systems, a pavement system is a complex, long-lived system. LCA practitioners should be aware that inherent uncertainty exists in each process within the system, and the process of analyzing them. This uncertainty includes data variability, input uncertainty, and model imprecision *(1).*

Although LCI databases try to satisfactorily identify the environmental inputs and outputs of a product or process, these databases only represent a part of the real world. For example, if the gasoline inventory in an LCI database is based on one particular brand of gasoline that is available in a particular market, the database might not fully represent the gasoline used in a study in a different market. For this reason, LCA practitioners often find themselves unable to obtain an LCI data source that is identical to that specific of their project. To account for this discrepancy, LCA practitioners should therefore carefully choose an LCI database that includes the products closest to those used their project, document the differences between the LCI data source and the actual items they used, and describe the limitations on their project created by use of this LCI data source. To minimize this type of discrepancy, LCA practitioners may use LCI data that are similar to the actual material used in the field and adjust data within a bounded range, then use a statistical tool such as a Monte Carlo simulation to assess the discrepancy.

Trying to predict the future introduces another source of uncertainty into the life cycle assessment of a pavement system. Traffic is often omitted from pavement LCA studies, presumably due to the complexity in modeling traffic and the effect of pavement design on traffic and vehicle performance. However, when it is included, traffic can be the largest contributor to environmental impacts. Thus, it should not be omitted unless a study is comparing two different pavement designs that share every other attribute (a rare situation). *Scenario analysis* can be used to assess uncertainty in the prediction of key parameters in the Use Phase, such as traffic flow and vehicle technology.

Model imprecision is caused by limits in knowledge. For example, although many researchers have striven to understand the role that pavements play in contributing to the urban heat island effect, it is still not fully understood. Similarly, network-level traffic effects remain too complex to model with current tools. Limits in LCA methods and theory can also increase uncertainty. *Co-product* allocation methods, for example, can influence the outcome of a study, but consensus on appropriate methods and differences at the level of fine detail can alter the allocation of burdens to a co-product.

The development of detailed models may reduce the uncertainties that arise from a lack of knowledge. In addition, scenario analyses of alternate theories or methods can test the robustness of study outcomes. A summary of all these uncertainty types and recommended treatments appears in Table 1.

Table 1: Summary of Treatments for Uncertainty in Pavement LCA

Types of Uncertainty	Recommended Treatment(s)
Data limitation - Geographic relevancy - Variance in material production processes (due to geography or age of data)	- Data collection for improved LCA datasets - Use of bounded ranges - Stochastic methods
Uncertainty in predicting the future - Traffic patterns, growth, and vehicle fleets - Technology advancement	- Scenario analysis or sensitivity analysis
Limits in knowledge, theory, or methods - Urban heat island - Co-product allocation - System-wide effects on traffic network	- Careful inclusion of complex processes and limiting the strength of conclusions based on those processes - Scenario analysis of alternate theory or methods

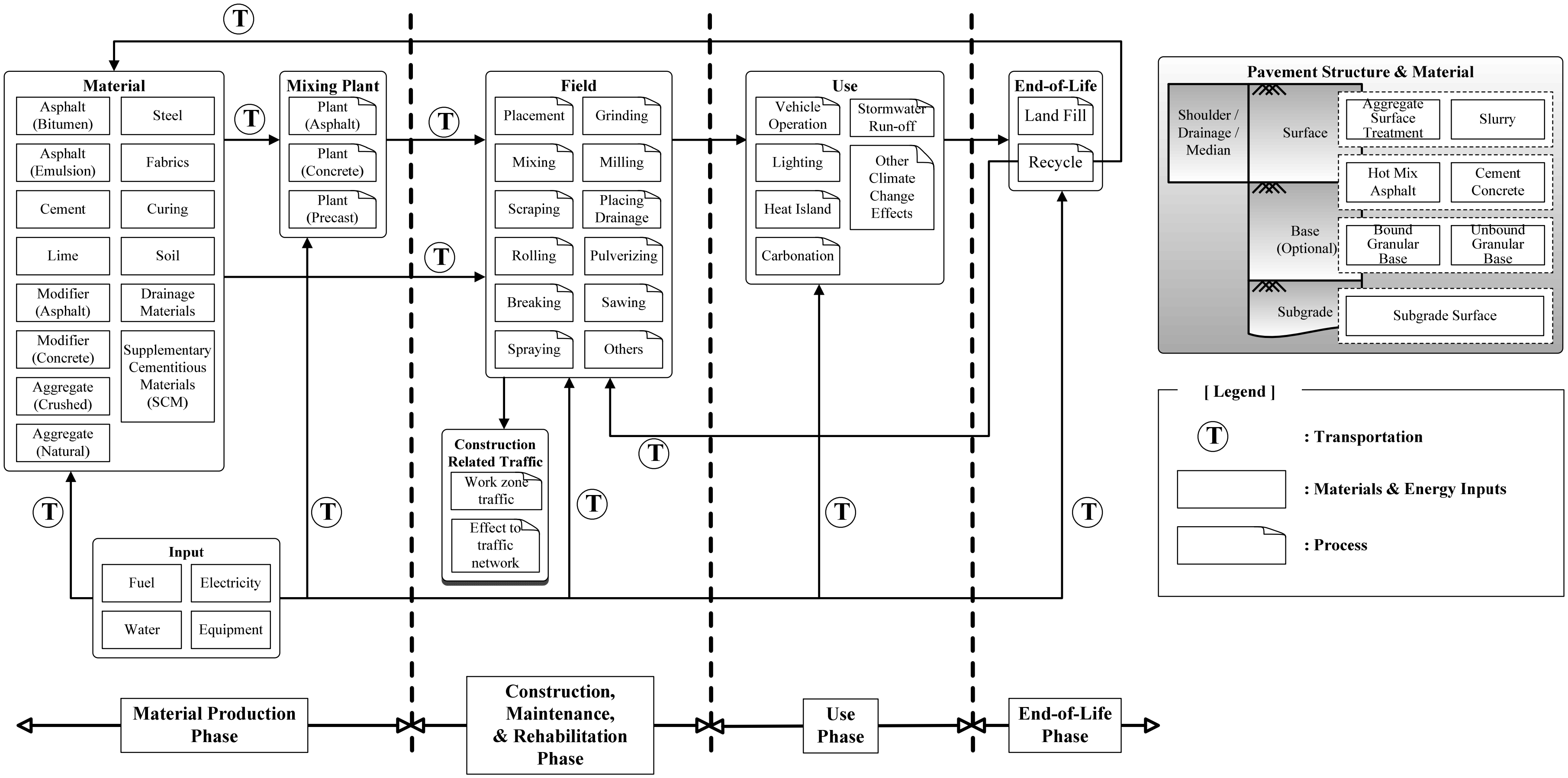
However, "location" and "time" are two principal domains where most of the uncertainty resides in a pavement LCA study. Because design and construction processes are influenced by local practice and policy, and a design's performance will be affected by local climate, traffic patterns and growth, and vehicle mix, the outcome varies from place to place. At the same time, a pavement system is unlike most consumer products, and it has a decades-long service life that makes it difficult to predict how the system will perform and what situations it will endure over the long-term.

LCA practitioners should have a clear vision of the project in order to properly characterize uncertainty. The following are guidelines for treating uncertainty in a pavement LCA:

- Determine a clear functional unit, system boundary, and goal, which will allow identification of sources of uncertainty.
- Take a transparent approach that will allow other researchers to improve upon the study as data improves and methods advance.
- Include scenario and sensitivity analyses that can test the robustness of the LCA modeling.

Figure 2: Proposed Framework for Pavement LCA[3]

Prepared by the Pavement LCA Group at UCPRC[4]



[3] The lists shown in the figure are not intended to be comprehensive or exhaustive.
[4] *Revised, August 22, 2011.*

PART 2: RECOMMENDED MODELS AND DATA SOURCES

This part of the *UCPRC Pavement LCA Guideline* provides a more in-depth discussion of the models and life cycle inventory (LCI) data sources for each pavement life cycle phase, and focuses on California and the U.S. Guidelines for choosing the models and data sets that can be used in a pavement LCA are also provided so that tools with similar functions can be selected for different regions. Gaps between current knowledge and analysis requirements are also listed where they have been identified. Future work will focus on these gaps.

1. Material Production Phase (Materials and Processes)

1.1 Materials

The materials used in pavement include but are not limited to asphalt, asphalt emulsion, asphalt modifiers, Portland cement or other hydraulic cement (e.g., calcium sulfoaluminate cement used in California, among many others), limestone, cement modifiers, hardrock aggregate, non-hardrock aggregate, supplementary cementitious materials (SCMs, including slag, fly ash, silica fume, and calcined clay), steel, fabric/fibers, drainage material, and soil.

1.2 Plant Processes

Asphalt concrete mixing, hydraulic cement concrete mixing, cement concrete precasting

1.3 Pavement Layer and Material Options

Before an LCA for the pavement is performed, pavement structure design must be considered. Table 2 shows potential pavement layers and the related options for material selection.

Table 2: Pavement Layer and Material Options

Pavement Material Options (Bonding and curing materials implied)	Potential Pavement Layer
HMA	Surface or base
PCC	Surface or base
Bound granular base (cement-treated base, asphalt-treated base, etc.)	Base
Unbound granular base	Base
Aggregate surface treatment	Surface
Subgrade	Subgrade
Slurry	Surface

1.4 Supplemental Considerations

Because a specific layer (e.g., an HMA layer) could be considered as a surface layer in one construction event and then as a base in a future one, it is important to document the cross section of the pavement before each event. In a situation where the underlying layer is unclear, it is also important to document the "assumed" underlying structure.

2. Construction Phase and Maintenance and Rehabilitation (M&R) Phase

The impacts to be considered during the Construction Phase include the fuel use and emissions contributed by both construction equipment and construction-congested traffic. Fuel use must always consider the life cycle emissions of fuels. Figure 3 shows the recommended analysis procedure.

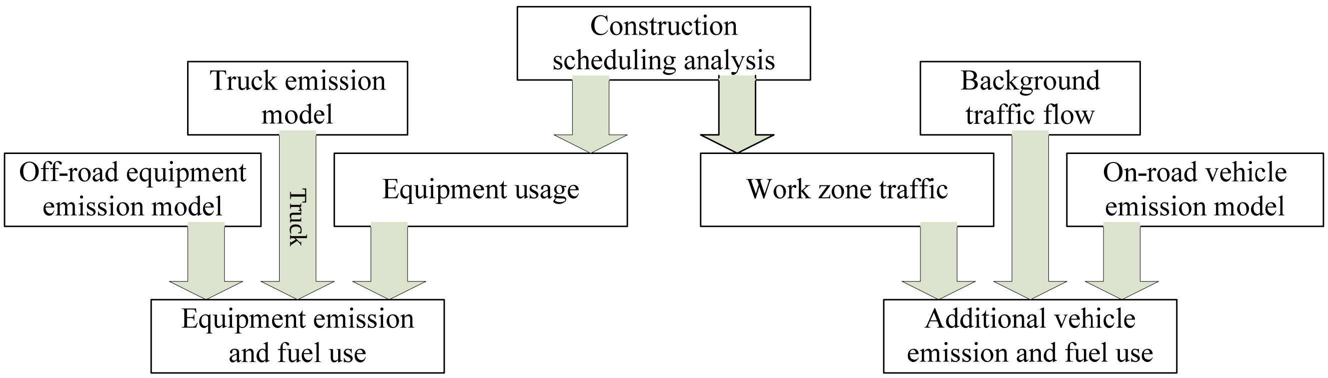


Figure 3: Recommended analysis procedure for fuel use and emissions in the Construction Phase.

2.1 Field Processes

The field processes during construction include but are not limited to transport, excavating, paving, placement, rolling, grinding, pulverizing, breaking, mixing, milling, sawing, scraping, spraying, and placing drainage.

2.2 Equipment Emissions and Fuel Use

The construction schedule, including its traffic closure pattern and equipment utilization, can be modeled using the software program *CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) (9)* or a similar program. *CA4PRS* is a tool that supports the integrated analysis of project alternatives for different pavement designs, construction logistics, and traffic operation options. The program provides a selection of construction equipment and activities, which then can be applied with the emissions factors obtained from a model such as California's *OFFROAD (10)*—a software application used to generate emissions inventory data for off-road mobile sources (e.g., a paver or excavator)—and then used to calculate fuel consumption and emissions. For states other than California, the U.S. EPA's *NONROAD2008a* model (*11*) can be used to calculate air pollutants from *off-road equipment.* For non-U.S. studies, models with similar functions should be used.

Currently, *CA4PRS* can provide the work zone analysis for six types of rehabilitation work, including HMA/RHMA overlay, full-depth HMA/RHMA replacement, mill-and-fill HMA/RHMA rehabilitation, continuous reinforced concrete pavement (CRCP) rehabilitation, jointed plain concrete pavement (JPCP) rehabilitation, and pre-cast pavement rehabilitation. An analysis for lane widening is under development as of this writing.

Gaps:

a) In general, construction processes that are not currently in *CA4PRS*, such as whitetopping or slab replacement, or other construction schedulers require further investigation. Requesting diaries from similar projects and applying their information is one option for modeling construction processes that are not already defined in a construction schedule model. This would allow LCA practitioners to analyze the schedule of these excluded maintenance and rehabilitation options.

2.3 Additional Emissions/Fuel Use from Construction-Related Traffic

Construction-related traffic includes work zone traffic and the overall effect on the network from construction congestion, such as detours. Currently, only work zone traffic is included for analysis.

Traffic behavior at the work zone, which is another output from work zone modeling and simulation, together with the *normal traffic flow* information, is used as an input for modeling motor vehicle emissions/fuel consumption. Because traffic behavior is a region-specific issue, special attention needs to be paid to the composition of the vehicle fleet and speed distribution. Sensitivity analysis is recommended regarding changes in fleet composition, speed distributions, market penetration of new vehicle technologies, and changes in vehicle fleet fuel consumption characteristics.

The current model for on-road motor vehicle emission/fuel consumption in California is *EMFAC* (Emission FACtors) *(12)*. *EMFAC* can calculate emission/fuel consumption rates from all motor vehicles, from passenger cars to heavy-duty trucks, operating on highways, freeways, and local roads in California. For states other than California, the U.S. EPA’s *MOVES* (Motor Vehicle Emission Simulator) model (*13*) may be used for on-road mobile-source emissions. As of this writing, the current version of *MOVES* is ver. 2010a.

Gaps:

a) *EMFAC* requires a speed spectrum to calculate vehicle emissions; however, the work zone traffic analysis in *CA4PRS* doesn’t calculate a speed distribution. Further information is needed to carry out the calculation.
b) *EMFAC* only considers a static traffic speed; however, vehicle acceleration and deceleration in congestion contributes to additional fuel consumption. This shortcoming would lead to an underestimation of fuel consumption in stop-and-go congestion. Because U.S. EPA’s *MOVES* has the ability to analyze this traffic condition, the application of *MOVES* in work zone traffic will be the focus of future work.
c) The effect of construction congestion on the network could also lead to additional emissions and fuel use. This problem needs further investigation.

3. Use Phase

3.1 Additional Vehicle Operation—Fuel Consumption

This current analysis only proposes to examine use from the perspective of fuel consumption from vehicle operations, which are affected by rolling resistance. Pavement deterioration increases rolling resistance—and thus lowers fuel economy and increases the energy consumed by traffic. The effect of rolling resistance can be accounted for by making it a parameter in estimating fuel economy because pavement condition can be modeled and estimated through pavement performance modeling. By taking this approach, additional fuel consumption due to deteriorated pavement can be evaluated through the change in pavement condition over the long run. One tool for evaluating this relationship is *HDM-4* (Highway Design and Maintenance Standards Model–ver.4), modeling software developed by PIARC (World Road Association) to conduct cost analysis for the maintenance and rehabilitation of roads *(14)*. *HDM-4* has an internal model to simulate the deterioration of pavement conditions and a mechanism to calculate vehicle energy consumption from IRI (International Roughness Index). The MIRIAM project will also produce further insights into this relationship between pavement condition and fuel economy (*15*). Also, traffic attributes, such as its composition and speed distribution, and new vehicle technologies need to be included in the analysis.

Gaps:

a) Our understanding of the relationship between pavement surface characteristics and vehicle fuel consumption is still in development. The current models require improvement.

b) Our understanding of differences in vehicle fuel consumption on different pavement types is still in development, and if significant differences exist, these need to be added to the models.

c) As with construction-related traffic, further investigation is needed to address the effects of congestion stop/start traffic speed distributions on fuel economy in the Use Phase.

d) Tire wear and damage to freight and vehicles due to pavement deterioration need to be determined.

3.2 Urban Heat Island

Two mechanisms have been identified as influencing urban heat island effects: albedo (solar reflection) and evaporative cooling. Differences in the albedo of pavements lead to different pavement temperatures, which then change air temperature. This change can result in additional energy use (such as that caused by increased use of air conditioning or other means for cooling warm air, or by both) or energy offset in buildings or vehicles.

Nearly all traditional pavements are impermeable, which means that they cut off the soil underneath from exposure to air, thereby preventing trapped moisture from evaporating into the near-surface atmosphere. However, a new type of pavement referred to as *fully permeable pavement* (also referred to as *pervious pavement* or *porous pavement*) allows the subgrade to contact air through the pavement. It is possible that this new pavement type's high porosity might yield a smaller heat island effect than traditional impermeable types because the water that can now evaporate in the air over the pavement might result in evaporative cooling.

The Heat Island Group at Lawrence Berkeley National Laboratory (LBNL) has conducted many studies on this topic and developed a semiquantitative relationship which characterizes air and pavement temperature (*16-17*). Future work would focus on how to convert the air temperature change to the related systemwide energy consumption change.

However, because the current understanding of this effect from pavement is still limited and the uncertainty of the test and modeling results is very high, when the urban heat island effect is considered in an LCA study, application of the following principles is recommended:

- Albedo is not the only factor that affects ambient temperature. Surface impermeability is also an important factor to be analyzed, and there are other microclimate-related factors that may be as or more important than albedo.
- Include the effects of pavement temperature and reflectance as parameters in a sensitivity analysis.
- If the pavement contribution to heat island effect and these other effects are considered, they must be specific to the study location, which must be explicitly defined in the study's documentation, and they must be documented (energy use by buildings, etc.).
- Albedo changes over time, so multiple measurements taken over a period of time, in addition to those taken at initial construction, need to be included in the analysis.

Gaps:

a) Albedo is highly affected by pavement aging. The mechanisms controlling albedo and pavement aging are not fully understood. Further, new technologies affecting long-term albedo are under development including the use of photocatalytic surfacing.

b) More field tests are needed to determine the coefficient in the albedo/temperature relationship, and the result will be highly dependent on air movement.

c) Currently there are limited studies on the evaporative cooling effect of pervious pavement. More studies are needed to address this issue.

d) Currently, cool pavement research is predominately U.S.-focused and a majority of the relevant research has been performed by the Heat Island Group at the LBNL. This has resulted in a concentrated field of research centered on North America (*18*).

3.3 Non-GHG Climate Change Effect

Currently only radiative forcing from albedo is considered. High albedo contributes to global cooling by reflecting a portion of incoming radiation back into space, thus producing a negative radiative forcing. The Heat Island Group at LBNL has also made an attempt to quantify the relationship between changes in albedo and offset in CO_2 equivalents (*19*).

Gaps:

a) A study modeling the albedo–radiative forcing relationship at the Heat Island Group of LBNL is still in an early stage and needs further development.

3.4 Water Pollution from Leachate and Runoff

Pollutants in groundwater may be modeled through programs such as *IWEM* (Industrial Waste Management Evaluation Model) (*20*), a software program developed by the U.S. EPA to model the transport and fate of waste constituents through subsurface soils and groundwater to a well.

Gaps:

a) Identify a model with a function similar to *IWEM* for tracking the transport of pollutants to *surface water*. The pollution in surface water is often a more critical environmental problem caused by *stormwater runoff.*

b) Different pavement designs have different effects on the deposit and transport of pollutants in water and changes to the water temperature. How to characterize the differences in pollutant movement among different pavement systems needs further investigation.

4. End-of-Life Phase

When a material reaches its end of life, there are typically two disposal options: recycling it or sending it to a landfill.

4.1 Recycling

Recycling of a pavement system requires the input of virgin materials (bitumen, cement, aggregate, additives, etc.) and the input of energy, and, as with any process that involves resource and energy inputs and results in emissions outputs, a burden on the environment is created. In determining a recycling component of pavement LCA, it is advisable to combine the burdens of producing the original system (with its virgin materials) and of the recycling process, and then to allocate part of the total to the original system and the rest to future pavements that will use the bulk of these materials and substructure.

Häkkinen and Mäkelä *(21)* considered allocation of recycled materials, and assumed that each construction event is only responsible for the materials it uses. This implies that the first construction event will take all the environmental burdens derived from using virgin material, and the subsequent construction events will only take the environmental burdens due to the processing and transporting of recycled materials. The report did not consider the environmental impact of waste.

Recognizing that recycled materials systems benefit from the original production of materials or systems, Ekvall *(22)* proposed a method that evenly allocates half the burden of virgin material production and final end-of-life waste to the first construction event and half to the final construction event. Similarly, the method also allocates half of the environmental burdens of recycled material treatment to the preceding construction and half to later construction.

Among the potential obstacles to implementing Ekvall's proposal is its requirement that LCA practitioners accurately predict the number of times a material will be recycled and the fate of those recycled materials. Thus, it requires a method that can accommodate the modeling of a specific construction event or site. To minimally accomplish this, a practitioner of pavement LCA can use average recycling rates to credit a pavement system with recycled material. However, practitioners should be aware that recycling rates may increase over time, so using current values may underestimate the actual rate at the time of recycling.

Gaps:

a) Although there are several ways to handle the allocation during recycling, future study is needed on selecting a widely accepted allocation method.

b) For some materials, such as milled asphalt pavement used as base, the handling of quality loss during recycling will be another focus for future study.

4.2 Landfilling

Impacts from landfilling include the burdens of transporting waste to the landfill site and leaching from waste once it is deposited there. However, most construction and demolition (C&D) waste is inert, so leachate is not likely to be a problem. The U.S. EPA conducted a study on water quality around C&D landfill sites and found that fewer than one percent of sites showed any water quality impacts (*20, 23*). Therefore, the impacts from waste transport will likely be the dominant effect of the landfilling process.

Gaps:

a) Studies are needed to determine whether the water problem from landfilling sites is really negligible compared to the transport process.

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PART 3: PAVEMENT LCA CHECKLIST

This “Pavement LCA Checklist” is part of the *UCPRC Pavement LCA Guideline*. It has been developed to help pavement life cycle practitioners prepare and organize essential information before conducting an analysis. It can also be used by LCA reviewers to identify differences among the basic elements of an LCA (such as system boundary or data source) and among different studies. It was prepared by the UCPRC LCA Research Team and was reviewed at the Pavement LCA Workshop held in Davis, California, in May 2010, with review comments included in the version shown here.

1 Goal and Scope Definition

1.1 Goal Definition

Study level (Choose one): ☐ Network level ☐ Project level

LCA type (Choose one): ☐ Single stand-alone LCA ☐ Comparative LCA

If “Comparative LCA” is selected, state the components that are assumed to be the same across systems:

1.2 Functional Unit

1.2.1 Physical dimension

Lane length: ______km — Suggested: Max 100 km; Min 0.5 km

Lane width: ______m

Number of lanes:

Including shoulder: ☐

If lane length, width, and number are not applicable, use total area: ______m^2 — Such as parking lots, airports, or intersections.

1.2.2 Performance requirements

Functional design life: _____years

Truck traffic (AADT):

Climate:

Subgrade type:

Criteria for functional performance: _______ , _______ ,

1.3 Analysis Period

Method used to determine analysis period:

Analysis period: _____years

1.4 Life Cycle Inventory

1.4.1 Primary energy: ☐

Clearly distinguish between feedstock energy and combusted energy: ☐

1.4.2 Greenhouse gases ☐

CO_2: ☐ CH_4: ☐

N_2O: ☐ Other:

1.4.3 Material flows ☐

1.4.4 Air pollutants

O_3: ☐ PM_{10}: ☐

$PM_{2.5}$: ☐ SO_2: ☐

CO: ☐ Lead: ☐
Volatile organic compounds: ☐ NO_X: ☐
Others: _______, ________,

1.4.5 Water pollutants ☐
1.4.6 Solid waste flows ☐
1.4.7 Other inventory categories ________, ________,

1.5 Pavement Structure Design and Life Cycle Phases

1.5.1 Pavement structure design (for each system)

Surface: ☐ Shoulder: ☐
Base or subbase: ☐ Drainage: ☐
Subgrade: ☐ Roadway lighting: ☐

1.5.2 Material Production Phase

Raw material #1 [List each of them]:

Material production: ☐
Feedstock energy: ☐
Transport of materials to site: ☐

1.5.2.1 *Engineered material*

Mixing in plant (HMA or PCC): ☐

1.5.3 Construction Phase and Maintenance and Rehabilitation Phase

Transport of materials to site: ☐
Transport from/to plant: ☐
Transport of recycled material: ☐
Equipment usage: ☐
Water use: ☐
Work zone traffic congestion: ☐
Vehicle technology change: ☐
Traffic growth: ☐
Lighting energy, if at night: ☐
Movement of equipment: ☐
Temporary infrastructure: ☐
Equipment manufacturing: ☐
Factory or plant construction: ☐

1.5.4 Use Phase

1.5.4.1 *Vehicle operation*

Impact to fuel economy from roughness: ☐ Damage to freight: ☐
Damage to vehicle: ☐ Vehicle tire wear: ☐
Traffic growth: ☐
Change in vehicle technology: ☐

1.5.4.2 *Heat island* ☐

1.5.4.3 *Non-GHG climate change mechanism* ☐

1.5.4.4 *Water pollution from runoff* ☐

1.5.4.5 *Roadway lighting* ☐

1.5.4.6 *Carbonation* ☐

1.5.5 End-of-Life Phase

1.5.5.1 *Recycling* ☐

Allocation: ☐

1.5.5.2 *Landfill*

Hauling of materials: ☐
Long-term water pollution: ☐

1.6 Impact Assessment

1.6.1 Global Warming

Global warming potential (GWP): ☐

Source : ☐ IPCC TAR ☐ IPCC AR4 ☐ Other

Time horizon (e.g. 100-yr, 20-year, etc.):

1.6.2 Other impact categories (List one by one.)

Impact category indicator:
Source for calculation:

1.7 Sensitivity Analysis

1.7.1 Variables

Variables that are used to perform sensitivity analysis: ________, ________, ________, ________, ________,

2 Models and Data Sources

2.1 Material Production

2.1.1 Material LCI (List all the LCI sources)

LCI source #[1,2,…,n] name:

Type: ☐ LCI Tool (refers to database from company or research organizations)
☐ LCI Study (refers to publish journal paper or study report)

Meet ISO standard? ☐
Data quality evaluation: ☐
Statistical analysis: ☐

2.2 Construction

2.2.1 Maintenance and rehabilitation schedule

Determined from:

2.2.2 Equipment use ☐

Construction schedule analysis: ☐ Data source: Model:
Equipment emission: ☐ Data source: Model:
Equipment fuel use: ☐ Data source: Model:
Truck emission: ☐ Data source: Model:
Truck fuel use: ☐ Data source: Model:

2.2.3 Construction-related traffic ☐

Work zone traffic analysis: ☐ Data source: Model:
Traffic network analysis: ☐ Data source: Model:
Additional emission: ☐ Data source:

		Model:
Additional fuel use:	☐	Data source: Model:

2.3 Use

2.3.1 Vehicle operation Pavement performance model:	☐	Data source:
2.3.1.1 Impact to fuel economy Pavement – fuel use model:	☐	Data source:
2.3.1.2 Damage to vehicle Pavement – vehicle model:	☐	Data source:
2.3.1.3 Damage to freight Pavement – freight model:	☐	Data source:
2.3.1.4 Vehicle tire wear Pavement – tire model:	☐	Data source:
2.3.2 Urban heat island		
2.3.2.1 Albedo effect	☐	
Pavement aging – albedo model:		Data source:
Albedo – heat island model:		Data source:
Heat island – energy consumption relationship:		Data source:
2.3.2.2 Evaporative cooling	☐	
Evaporation – heat island relationship:		Data source:
Heat island – energy consumption relationship:		Data source:
2.3.3 Non-GHG climate change effects		
2.3.3.1 Albedo – radiative forcing	☐	
Albedo – radiative forcing model:		Data source:
Radiative forcing – GWP relationship:		Data source:
2.3.4 Leachate Pollutant transport model:	☐	Data source:
2.3.5 Carbonation Carbonation model:	☐	Data source:
2.3.6 Roadway lighting Electricity use model:	☐	Data source:

2.4 End-of-Life

2.4.1 Recycling Method used to allocate input and output:	☐	
2.4.2 Landfill	☐	
2.4.2.1 *Truck use*		
Truck emission:	☐	Data source: Model:
Truck fuel use:	☐	Data source: Model:

SECTION III: PAVEMENT LCA WORKSHOP DISCUSSION SUMMARY

Pavement Life Cycle Assessment Workshop, Davis, CA, May 2010

This summary has been produced to condense the content of the break out discussions that were part of the UCPRC Pavement LCA Workshop. It highlights some of the discussions that occurred during each breakout session and presents responses and decisions made by the UCPRC Pavement LCA Research Team regarding suggested research products.

Process Used to Produce this Summary

On Day Two of the workshop, three breakout sessions were held with the participants divided into groups where they stayed the entire day. This was done so that each group would have a measure of diversity in its background and expertise. During each session, each group was given one question. Some of these questions were given to multiple groups to ensure that a wide range of discussions occurred.

To help improve the research products and to achieve the desired outcomes of the workshop, a member of the workshop organizing team took notes during these discussions. These notes were then condensed into summary slides and presented for discussion by all attendees on workshop Day Three. The notes from the breakout sessions were later written up and edited into this document by the workshop organizers.

Summary Organization

This summary was organized by the UCPRC Pavement LCA Research Team around questions that were initially posed to one or more breakout session groups. The main points of discussion for each question have been itemized and are followed by key outcomes from the discussions. These are followed by the research team members’ responses and summaries of their planned follow-up actions.

Question #1: Are there any critiques of the proposed framework, especially of the following aspects?

- **Goal (focus on scale and purpose)**
- **System boundary**
- **Functional unit**
- **Assumptions**
- **Recommended models and data sources**

Main Discussion

Participants generally agreed to the structure of the proposed framework with some recommended changes, and repeatedly emphasized the importance of having a clear goal and scope. A physical dimension for the functional unit, a key component of the scope, was not agreed upon as some group members indicated that a unit based on lane-km could not be generalized to different types of pavements; for example, although a lane-km unit might work for a highway system, it would not necessarily work for streets, parking lots, airports, and other pavement applications. In addition, a few group members suggested defining functional units on a square-meter (m^2) basis.

Key Outcomes

1. There are two levels of LCA studies, i.e., network level and project level, and the distinction between them should be clarified.
2. The proposed framework refers to a project-level LCA. A guideline for a network-level LCA should be developed.
3. The framework should include the site design, not just the pavement design (e.g., location of batch plant).
4. Pavement performance requirements/functional design life needs to be more clearly defined in the framework.
5. Need to set up the standard unit that output is based on.
6. The diagram provided in the framework needs to include an exhaustive list of construction materials and a comprehensive list of environmental loads.
7. Need to split maintenance and rehabilitation into separate parts.
8. Equipment manufacturing and capital investments dedicated to the construction process should be included.
9. Consider including transportation of workers and support from service sectors.
10. ISO 12006 has been recommended for review to refine the proposed framework.

UCPRC Responses

To Numbers 1 and 2 above: The language has been revised to better reflect the difference between them. Also, the *UCPRC Pavement LCA Guideline* is intended to guide project-level studies; however, the network effects incurred by a project, such as the effect on the network of work zone–induced traffic, should be included when data and models are available.

To Number 3: General site work is included in the construction phase, such as the location of the batch plant. Also, text has been provided at the beginning of the framework to address the difference between roadways and pavement. This framework is only intended to guide pavement LCA studies, so site design elements such as signs and striping are not included.

To Number 4: The detail and specificity of pavement performance requirements have been enhanced.

To Number 5: This concern is addressed through the functional unit. All outputs of an LCA are based on the functional unit.

To Number 6: The diagram is intended solely as an example and not to provide an exhaustive list of pavement materials, in part because the variety of pavement materials is nearly infinite and no list could be truly comprehensive. The *UCPRC Pavement LCA Guideline* requires inclusion of all materials used in the pavement. Similarly the list of environmental loads is dependent on the goals of the LCA study and is likely to change over time. The Pavement LCA Checklist that was developed includes suggested environmental impact categories.

To Number 7: It is recommended that each construction, maintenance, or rehabilitation event be modeled separately in the study, but in terms of system boundaries they are essentially the same. For this reason they are considered in the same section of the guideline.

To Number 8: The manufacturing and capital investments attributable to the particular construction event are within the system boundary.

To Number 9: Transportation of workers has been excluded and no proposal for its general inclusion has been given because currently the difference between their typical driving activity and their travel to a specific construction site is not yet understood. However it may be included in cases where it appears to be important; for example, it may be included if a construction site is in a remote place or if alternative modes of transport or other efficiency actions (e.g., carpooling or busing) for workers are being implemented. Support from service sectors is treated similarly.

To Number 10: The UCPRC research team is currently reviewing the potential applicability of ISO 12006 for this framework.

Question #2: How can bitumen feedstock energy be dealt with in a pavement LCA? (*UCPRC Pavement LCA Guideline: LCA Framework and Standard Assumptions*, Section 4.1.) The problems considered under this question include:

1. **How could an LCA practitioner interpret bitumen feedstock energy?**
2. **When bitumen is considered as a fuel source, do its marginal emissions need to be considered? If so, how should they be incorporated into the analysis?**
3. **If an alternative upgrading of bitumen is taken into consideration, is it an important component? How could this component be included?**

Main Discussion

ISO 14044:2006 specifically requires that an LCA report on feedstock energy. However, questions arose as to what feedstock energy means for bitumen that would never be burned as a fuel source. Participants with experience in the asphalt industry tended not to treat bitumen as an energy source, arguing that it makes a very poor fuel, that bitumen used in pavements would never be combusted for its energy value, and that, in any case, California law prohibits direct combustion of bitumen. Furthermore, they noted that if bitumen were to be burned outside of California, it would need to be mixed with bunker fuel and could only be burned at sea. Lastly, they noted that energy from bitumen is not completely available for work.

Opponents argued that the “dirtiness” of bitumen is relative and that it is actually cleaner than coal.[5] Further, although bitumen is not commonly used as a fuel today, this does not mean that it might not become one in the future. Therefore, a compromise for LCA reporting might be the separation of feedstock energy from the other types of consumed energy.

Discussion participants were concerned about the focus on the feedstock energy of bitumen as opposed to feedstock energy of rubber and polymers, which should be treated similarly.[6]

Another question addressed by the groups pertained to the air pollutant emissions from burning bitumen—which is a essentially a consequential approach to treating bitumen feedstock energy. It was argued that if bitumen were ever to be used as a fuel source, the emissions would result due to upgrading and combustion; however, if it were used solely as a material, then those emissions would be “prevented.” In response, some group members argued that the emissions should not be included, asserting that it is double counting to consider the “prevented”

[5] This reflects the perspective of some discussion attendants and has not been verified.

[6] However, to clarify, ISO 14040:2006 requires that feedstock energy be reported for all materials. This discussion likely reflects a participant’s misinterpretation of the ISO standard.

emissions since they are only figurative, and this reflects the viewpoint an attributional LCA approach. After some discussion it was agreed that whether or not these emissions are to be included will essentially depend on the type of LCA approach selected—consequential or attributional—and that this should be clearly stated in the goal of the study.

Group consensus settled on the following: Whenever feedstock energy or marginal emissions are reported in the LCA, they should be reported separately from the rest of the energy and emissions.

An alternative to burning bitumen directly is to further upgrade it to lighter fractions. Some group members questioned whether the "recoverable" energy could be addressed in feedstock energy values. It was suggested that only the net energy available after upgrading should be accounted for. The *coking* process is the limiting factor for *upgrading bitumen*, and this process very energy intensive.

Furthermore, future studies need to pay more attention to asphalt refineries (which specialize in producing heavy products) since they, rather than integrated refineries, are now providing increasing amounts of bitumen. The group reached a consensus that energy for upgrading should be rolled into raw feedstock energy.

Finally, discussion turned to whether the problems involved in reporting and accounting for feedstock energy are confined to bitumen. Some group members argued that feedstock energy would not really be considered in decision-making, in part because its meaning is difficult to interpret. There was a suggestion that this question be brought to the ISO standards committee because the ISO may not have fully addressed the complexity of this issue.

Key Outcomes

1. Pavement LCA treatment of feedstock energy differs fundamentally from other forms of life cycle primary energy in two ways:
   a. It must be reported for a study to be ISO compliant; and
   b. The group recommended that feedstock energy be reported separately.
2. Because of the complexity and lack of consensus on how to report and account for feedstock energy, its consideration in the total energy consumption should be left up to the user.
3. Whether the emissions from potential use of bitumen as a fuel should be considered depends on the type of LCA: it should be considered if the LCA approach is consequential and excluded if it is attributional.
4. For future research, net upgrading impacts could be calculated for possible inclusion in LCA, in addition to reporting the feedstock energy in its entirety.

UCPRC Responses

The research team will report bitumen feedstock energy in the *UCPRC Pavement LCA Guideline* documents in order to be compliant with ISO guidelines. Bitumen feedstock energy will be reported separately from other types of energy. It will be left to the decision-maker whether or not bitumen feedstock energy should be considered in decision-making for LCA studies conducted for California and other locations where use of bitumen as a feedstock energy source is highly unlikely over the time horizon of the LCA study.

Question #3: How can the relationship between surface characteristics and rolling resistance be handled in a pavement LCA? (*UCPRC Pavement LCA Guideline: LCA Framework and Standard Assumptions*, Subsection 5.4.1.1.) The problems considered under this question include:

- **Do we have the right models?**
- **Is there adequate information that allows inclusion of the Use Phase in the life cycle of pavement?**
- **Beyond direct fuel use, where should the system boundary be drawn regarding vehicle operating effects?**
- **In the *UCPRC Pavement LCA Guideline*, is the modeling approach outline adequate for considering traffic flow (i.e., congestion, acceleration, and deceleration)?**

Main Discussion

Groups addressing these questions reached consensus that the *HDM-4* model is acceptable for modeling the effect of pavement surface characteristics on vehicle operating conditions. However, group members recommended that *HDM-4* would be better if more mechanistic features, such as speed fluctuation in *congested traffic flow*, were introduced into the model. This change would result in a more flexible model that could adapt to inevitable changes, such as new vehicle technology.

Discussion participants pointed out that pavement-related information (i.e., IRI, rut depth, and texture depth) is easier to collect than vehicle information. Thus, while pavement performance can be reliably modeled, this may not be the case for predicting future traffic loads and vehicle technology.

With respect to system boundary, one group member felt that expanding it beyond the direct effect of surface texture on fuel consumption would complicate the problem and so it should not be undertaken. However, groups agreed that a broader system boundary should be left as an option in order to support more comprehensive LCA and impact categories (e.g., noise, damage/cost to goods, damage/cost to vehicles).

Group members found consensus regarding inclusion of congestion in the LCA framework.[7]

Key Outcomes

1. The calibrated *HDM-4* model is currently acceptable for modeling the effect of pavement surface characteristics on vehicle operating conditions.
2. Parameters that are difficult to predict accurately, such as vehicle technology and future traffic information, should be considered in sensitivity analyses.
3. The condition of "congested traffic flow" should be included in the analysis.

UCPRC Responses

The research team will do the following:

- Use the *HDM-4* models for initial studies until better models are available, and pay particular attention to new information coming from the MIRIAM project.
- Leave construction work zone traffic in the LCA Framework.
- Pay particular attention to the composition of the vehicle fleet and speed distributions for particular LCA studies.
- Recommend sensitivity analyses regarding changes in fleet composition, speed distributions, and market penetration of new vehicle technologies, and changes to vehicle fleet fuel consumption characteristics.
- Further investigate the effects that stop-and-go driving in congested traffic settings have on fuel economy, and consider congestion in the Use Phase.
- Add noise, damage/cost to goods, and damage/cost to vehicles as options to the LCA Framework, depending on the goals of the study.

Question #4: In what ways can LCA be incorporated into decision making?

Main Discussion

Generally, the discussion groups agreed that the *Pareto frontier* can be a potential approach for reconciling the economic and environmental objectives for regional planning. The three main points are summarized as follows:

Firstly, if research is not currently at the Pareto optimal frontier, current practice should be pushed to that frontier in order to maximize environmental savings. This may be an iterative process and difficult to get right initially.

[7] Construction work zone congestion is within the current LCA framework. Its effect on the relationship between surface characteristics and fuel economy has not yet been explored.

Secondly, another important aspect is that all points on the frontier should be assessed using the same scope, including discount rate, analysis period, system boundary, data, etc. Before using the frontier to make any decision based on economic and environmental objectives, the baseline, which is currently unknown, needs to be determined. Group members pointed out that the frontier may not be a smooth curve, and that it could be any shape, such as a straight edge or sawtooth.

Thirdly, group members also pointed out some broader conceptual problems with the Pareto frontier. For example, decision makers may not accept this approach to decision making. LCA outcomes will need to be presented as a single indicator of performance using weighting factors.

A weighting system like the one shown in the following table was suggested. This table provides for transparent reporting of the weighting factors and outcomes for each criterion. The transparency of this reporting method was seen by the group as an advantage of this approach. A sensitivity analysis is also very easy to perform based on this system. However, the group acknowledged that different agencies and stakeholders have different values, and thus the table may need to be adaptable. Another potential problem seen was the easy manipulation of this system.

	Init. Const.	**LCCA**	**Environmental Impact**	**Recycling**	**Maintainability**	**Total**
Weighting factor	60%	20%	5%	10%	5%	100%
HMA	total/ weighted	total/ weighted	total/ weighted	total/ weighted	total/ weighted	total/ weighted
PCC						
Structural						
Etc.						

In response to the problems identified with this weighting system, some people suggested that it only be considered as a framework, and that actual weighting factors should be created by individuals who are as close to the "front lines" as possible. Therefore, "the owner agency, rather than an environmentalist, politician, etc.," should make decisions regarding the weighting factors.

Caltrans currently bases weighting factors on environmental requirements, and this is already integrated into the CEQA process, etc. However, determining how LCA results will fit into this framework is unknown and requires further attention.

Finally, all the groups addressing this question agreed that for all the methods used to incorporate LCA into decision making, the most important factor is standardization. All the processes need to be standardized to minimize the risk of manipulation.

Key Outcomes

1. All of the points at the Pareto frontier should be acquired under a series of consistent conditions including but not limited to the goal, scope, and key assumptions, such as discount rate, system boundary, etc., to allow for equal comparisons.
2. If the weighting factor method is used to generate an indicator of performance for pavement systems based on the LCA results, then other externalities such as maintainability or recycling also need to be considered.
3. The LCA working group should provide a list of potential criteria for use in *multiple-criteria decision making.*
   a. The decision of which criteria to use and the weighting of those criteria should be made by the owner-agency.
   b. Owner-agency committees deciding on the weighting factors should be diverse enough to speak for the competing criteria.

UCPRC Responses

The research team will continue to explore multiple-criteria decision making through research and interactions with Caltrans for the state network and for local government in ongoing research projects. Multiple-criteria decision making will be considered in the LCA Framework; however, no specific recommendations will be made at this time. It is clear that this is an area that needs a great deal of additional work for the U.S. context.

Question #5: How to set the time horizon in a pavement LCA? (*UCPRC Pavement LCA Guideline: LCA Framework and Standard Assumptions*, Section 3.)

The *analysis period* refers to the time horizon during which the inputs and outputs associated with the functional unit for a system or systems are inventoried. The initial construction of each system will have a different functional design life, and may be followed by a series of different maintenance and rehabilitation (M&R) activities to preserve its function. Assessing the pavement system over a time horizon presents a major challenge. These are among some proposed approaches for determining the analysis period:

- **Using 1.5 times the longest functional design life among all alternatives**
- **Using the duration to the next major rehabilitation**
- **Annualizing/amortizing construction events**

Main Discussion

The group discussed two issues, the first of which was the definition of the *service life* of a pavement system and the second of which was the *analysis period.*

The discussion of service life mainly focused on defining the *end of service life.* Three options were suggested for this: (1) service life ends before demolition, (2) service life ends after demolition, or (3) service life ends after a major rehabilitation (reconstruction). All the group members agreed to include demolition in the service life, but did not agree about whether to include reconstruction.

The rationale for including reconstruction was that demolition and major rehabilitation often occur concurrently, which makes it hard to distinguish one from the other. If reconstruction is excluded from service life it becomes harder to capture the savings based on the recycling of material (leading to an allocation problem). The rationale for excluding reconstruction was that it might be the “cradle” for the new pavement system. However, members who spoke for excluding reconstruction also agreed that allocation of demolition/reconstruction should be properly analyzed.

It was generally agreed that the analysis period should be set up so that the study results can be compared with other studies, and that the analysis period should be in accordance with the goal and scope of the study. However, it was noted, the definition of service life affects the selection of an analysis period. Members who favored including reconstruction were more comfortable with setting up an arbitrary analysis period (e.g., 30 or 40 years). Members who favored excluding reconstruction liked the idea of having a common denominator across different pavement systems with different service lives. These members were comfortable with the idea of annualizing construction events, as well.

Key Outcomes

1. The service life of pavements should end after demolition, but whether it ends after major rehabilitation (reconstruction) needs further discussion.
2. The group agreed that the analysis period should be set up so that results can be compared across studies, and that the period should be in accordance with the goal and scope of the study. However, the group did not reach consensus on how to determine the analysis period for a pavement LCA.

UCPRC Responses

The research team has concluded that for most comparisons of alternatives, reconstruction and demolition should be considered in the life cycle because they are almost always concurrent (i.e., very few roads are demolished and then abandoned) and the amount of demolition is tied to the reconstruction strategy. However, when the time before reconstruction or a major rehabilitation (partial reconstruction) activity occurs is deemed to be extremely long (more than approximately 70 years)—which imparts a great deal of uncertainty to the future reconstruction (analysis period of 85 to 100 years)—then it is recommended not to include reconstruction/demolition.

In general, it is difficult to find a common denominator among the alternatives being compared and an arbitrary analysis period that is at least 1.2 to 1.5 times the length of the longest-lived recommended alternative. Once again, the analysis period decided upon should be in accordance with the goal and scope of the study. Because of the inherent difficulties and arbitrariness associated with selecting an analysis period, the rationale should be clearly described within the study's documentation, and sensitivity and/or scenario analysis should be considered.

Questions #6: How to deal with the allocation problem in recycling? (*UCPRC Pavement LCA Guideline: LCA Framework and Standard Assumptions*, Subsection 5.4.1.) How to deal with *down-cycling*, i.e., quality loss during recycling?

Pavement materials may be recycled on-site or through an off-site recycling system. In either case, allocating the burdens of recycled or repurposed materials to a specific pavement system is challenging. The following methods have been proposed in the LCA literature to address this challenge.

- **An allocation method that assigns each construction event with responsibility for the materials it uses (as was done in one of the studies considered).**
- **A 50/50 method that evenly allocates half the burden of producing and disposing of virgin materials to the first construction event and the other half to the final construction event, which uses recycled forms of the virgin material.**

Main Discussion

A 50/50 method has been used to allocate the environmental burden of recycled materials. The group indicated that this might be the result of uncertainty about how materials will be treated at their end of life. The following questions were used to address the question of recycled material allocation and its challenges.

1. *Q: What materials will be recycled in the future?*

   A: Materials that have not been recycled in the past may be recycled in the future.

2. *Q: How will materials be recycled?*

   A: Not every material can or will be recycled to the same state; that is, materials may be "down-cycled" to a lower-value material.

3. Q: Where will the materials be recycled?

A: At the project level, pavement materials will be recycled in-place, on-site, or off-site. At the network level, it is often uncertain where the materials (virgin or recycled) will come from, so the location of recycling is uncertain.

No consensus was reached regarding how to deal with the allocation problem in recycling, and the question was left unanswered. However, all the participants agreed that the 50/50 method is inappropriate due to its vagueness in the logic of allocation. Participants made several suggestions for replacing the 50/50 method:

1. Contractors will favor a method that counts recycled materials only when they are used or when the recycling process is conducted—this means that credits for future recycling or material recyclability will be ignored. This method is in accordance with current LCA practice.
2. Sensitivity analysis should be used to evaluate uncertainty.
3. Part of the future work needs to focus on allocation under the scenario where there are various products and logistics while at the same time the total cost of production is optimized.
4. Conduct case studies and explore how materials are actually recycled. This method will take time, effort, and money, but it will reduce uncertainty and provide an excellent foundation for allocation in pavement life cycle assessment studies as the number of case studies increases.

UCPRC Responses

The research team will follow all four of the key outcomes and include them in the *UCPRC Pavement LCA Guideline* documents. It will be recommended that the third and fourth outcomes be included in research road maps. (Note: These are similar to the recommendations of the recent NSF/FHWA Workshop on Pavement Sustainability[8].)

Question #7: How and when should the heat island effect be taken into account in pavement LCA? (*UCPRC Pavement LCA Guideline: LCA Framework and Standard Assumptions*, Subsection 5.4.1.2.)

- **How to model the consequences of energy and other emissions?**
- **How to validate the results?**

[8] Flintsch, G. International Sustainable Pavements Workshop. January 7-9, 2010. Dulles, VA, 2010.

Main Discussion[9]

Pavements contribute to the heat island effect because of multiple factors, including impermeability and albedo. Albedo is a measure of a surface's solar reflectivity, and differences in pavement albedo lead to different pavement temperatures, which then affect air temperature.

Traditional pavement structures are typically impermeable, which contributes to the heat island effect. Permeable pavement is a technology that can help mitigate this effect. The challenge in using this type of pavement is that it requires routine cleaning to maintain its permeability over time. However, there is another trade-off with use of this type of concrete because its albedo decreases as the structure ages; this is in contrast to non-permeable pavements, which increase their albedo with over time and mitigate the heat island effect.

One outcome of the heat island effect was increased energy consumption attributable to greater use of air conditioning in buildings and vehicles. In addition, the increase in temperature may affect pavement performance, such as rutting in asphalt pavement, high temperature gradient in concrete pavement, or changes in rolling resistance that impact the fuel economy of vehicles.

Another conclusion arrived at during the discussion was that a marginal change in temperature could lead to a significant energy saving. A group member pointed out that the heat island effect from pavement could be relatively small compared to other factors. However, because there was a steep curve between temperature and energy consumption from air conditioning, which is especially the case when the electrical grid is operating at peak capacity, and power plants operating at peak capacity are less energy efficient and may emit more pollution per kilowatt generated than plants operating at base load, even a 1°C drop in temperature can result in a significant potential energy saving.

There are several important aspects related to the heat island effect. The first is that pavement albedo changes over time: asphalt pavement lightens over time, increasing its albedo, while PCC darkens during its use, decreasing its albedo. The former is a result of aging asphalt, while the latter depends on the traffic volume on the pavement. The second important aspect is that this effect should only be taken into account for locations where air conditioning is used. [10,11] This point emphasizes that the effects of heat island formation are regionally

[9] The discussion only deals with the urban heat island effect and not radiative forcing from pavement reflection. There was some discussion of radiative forcing but it was generally agreed that research in that area was far from sufficient to include in a generally applicable pavement LCA at this time.

[10] The heat island effect could also provide a warming effect during winter months.

[11] While acknowledging that the heat island effect is a regionally specific concern, it should be pointed out that impacts from the effect exceed the energy problem attributed to air conditioning. Examples include these possible situations: a heat wave exacerbated by the effect might result in the deaths of people in apartments that do not have air conditioning; heat island effect–warmed stormwater run-off may disrupt the ecosystem of a stream or creek; ozone pollution may be exacerbated by the effect.

specific. Finally, the heat island effect should only be taken into account on a network or regional level[12,13], such as a city, because the heat island effect from a single section of pavement is not significant enough to change the temperature and energy use in a city.

With regard to how the heat island effect should be included in an LCA, one group that addressed this question reached the following consensus: If there is available research and data to describe the relationship between pavement characteristics and the heat island effect, then it definitely should be included. If there is no scientific consensus available at the time, then sensitivity analysis should be adopted. There are already some quantifiable relationships for the heat island effect, but the research is still not mature enough for clear integration into LCA. Therefore, their effect should be included in a sensitivity analysis, and only at the regional level.

Key Outcomes

1. Current models are adequate for and capable of exploring the heat island effect in LCA study. However, the heat island effect should be included in sensitivity analysis at the regional level.
2. The significance of the heat island effect relative to other impacts from pavement, such as fuel consumption in vehicle operation, is place-specific and its consequences (whether it benefits humans) are also region-dependent.
3. Changing albedo over time for different pavements or photocatalytic surfacing needs to be considered in LCA studies.

UCPRC Responses

The UCPRC Pavement LCA Research Team will recommend the following guidelines beyond the *UCPRC Pavement LCA Guideline*, which focuses on the project level:

- Albedo is not the only factor that affects ambient temperature. Surface impermeability is also an important factor to be analyzed, and there are other microclimate-related factors that may be as important or more important than albedo.
- Include pavement temperature and reflection effects as parameters in sensitivity analysis for pavement LCA.
- If the pavement contribution to the heat island effect is to be considered, its effects must be specific to the study location, which must be explicitly defined in the study's documentation.
- The specific effects of pavement temperatures and reflection considered in the study must be documented (energy use by buildings, etc.).
- Albedo changes over time, and thus the LCA should consider more than just the albedo at initial construction.

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[12] Our understanding is that currently there are potential reliable quantification methods, but they still need further research to be applied in a project-level LCA. An LCA study is needed to make sure that the benefit from cooler pavement is not offset by any other additional impacts imposed by cooler pavement itself.

[13] Although the *UCPRC Pavement LCA Guideline* is intended for project-level analysis, the discussion is for all pavement LCA-related topics so it is not restricted to project-level analysis.

Question #8: What are the questions faced by policy makers, and what outcomes from LCA are necessary to answer these questions?

Main Discussion

Some group members from agencies emphasized that the decision-making process will be based on need, constructability, cost, etc., and that therefore LCA should inform decision makers only regarding which option is not the "worst," rather than which option is the "best."

Participants were also interested in linking cost assessment and LCA results as a mechanism to ensure that pavement designs that achieve environmental goals do not compromise limited budgets (i.e., money and time). However, the group did not express a preference for alternative methods of environmental assessment, such as the point-counting approach used in the earlier version of LEED.

Agency participants also indicated that Caltrans has changed its indicator of environmental impact from GHG to equivalent barrels of foreign oil.[14]

Key Outcomes

1. How to incorporate LCA into a traditional project cost estimate is the biggest problem faced by decision makers.
2. Decision makers may prefer an alternative system to LEED, which is the currently used rating system.

UCPRC Responses

The research team will continue to discuss ideas with Caltrans, local California governments, and others. Also, the research team will recommend against implementation of a LEED-style rating system unless it meets these two conditions: it is calibrated (and updated) by LCA studies that are compatible with the *UCPRC Pavement LCA Guideline* or other documents that have gone through a similar critiquing process, and the procedure that the analysis follows is project/region/process-specific enough to avoid unintended negative environmental consequences.

[14] This comment by a participant was inaccurate and was introduced as part of a discussion about potential political changes that might affect pavement LCA studies. Caltrans has not made any decisions regarding criteria of this kind (GHG versus foreign oil) but has discussed alternatives.

Question #9: How would agencies implement LCA (e.g., Netherlands procurement policy)? What are the potential differences when LCA is implemented in *design-build* and *design-bid-build*?

Main Discussion

One possible way to implement LCA is by integrating it with LCCA and evaluating benchmark construction activities, such as rehabilitation or maintenance activities. As decision makers attempt to reduce life cycle cost (LCC), they can look at the environmental gains (or losses) associated with the change. Then environmental analysis and cost analysis can be carried out within the same framework, such as a Pareto frontier, or simply by analyzing the ratio between changes in costs and changes in an environmental attribute derived from a base case (changes in dollar versus changes in environmental impact).

It was suggested that both LCA and LCCA be required for each alternative so decision makers can see the trade-offs between economic costs (or savings) and GHG emissions, for example.

In a design-bid-build system (lowest initial cost bid) such as that used for most projects in California, LCA is best applied at the design stage. In a low-bid system, however, contractors may not follow the lowest impact construction processes. Therefore, the owner needs to specify the required process for design decisions, and this process will require a clear definition of environmental goals, such as performance criteria. Nevertheless, because it is still difficult to impose requirements on contractors' behavior in order to improve environmental performance (such as requiring specific equipment for construction,), there is a further need to educate the construction industry about it. Another option would be to implement an extra scoring system in addition to the low bid.

One problem for agencies is that at the design stage they have little or no idea where materials are coming from, which makes it difficult to estimate the inventory accurately. To achieve the *green construction* objective, some agencies set performance goals, such as local material sourcing, as a starting point.

With a design-build system, it is a challenge to verify whether LCA is being performed properly under time constraints because agencies do not get a final design until the proposal is ready. Although it is possible to set an environmental goal for contractors before construction, this will require that contractors evaluate the entire construction project from the life cycle perspective and be very creative in achieving the environmental goal.

In the discussion, group members pointed out that there is a need for the academic world to bridge the gap among agencies, owners, and consumers, and to educate them on their research findings through a program such as technology transfer.

Key Outcomes

1. There is a need to educate agencies, the construction industry, and consumers about LCA.
2. Environmental impact and economic cost should be evaluated under the same framework, such as a Pareto frontier in multiple-criteria decision making, or something similar.
3. LCA needs to be incorporated into the bidding process. In this way, it can influence contractors' bidding behavior and encourage innovation.

UCPRC Responses

The UCPRC Pavement LCA Research Team will pursue further educational outreach to state and local governments and to the pavement industry on the results of this project once the UCPRC obtains the initial results of other pavement LCA studies. The research team will continue to investigate and discuss ideas for implementing other environmental performance considerations in LCA—in addition to GHG emission and energy consumption—with Caltrans, local governments, and the pavement industry.

APPENDIX: LIST OF WORKSHOP PARTICIPANTS AND ORGANIZERS

List of Participants and Organizers, LCA Workshop, UC Davis, May 5 – 7, 2010

Name	**Organization**
Participants	
Janet Attarian	City of Chicago
Gina Ahlstrom	Federal Highway Administration, Pavement Technology
Mehdi Akbarian	Massachusetts Institute of Technology
Jim Andrews (Day 2 only)	Caltrans Environmental Analysis
Melissa Bilec	University of Pittsburgh
Karim Chatti	Michigan State University
Mike Cook	Graniterock Corporation
Bruce Carter	Hanson Aggregates West
Nick Coetzee (Day 1 only)	Dynatest Consulting, Inc.
Janko Cretnik	ZAG Slovenia
Imelda Diaz	County of Los Angeles Pavement Management
Barry Descheneaux	Holcim Corporation
David Edwards	California Air Resources Board
Jon Epps	Texas Transportation Institute
Gerardo Flintsch	Virginia Polytechnic Institute and State University
Florian Gschosser	Swiss Federal Institute of Technology Zurich
Joe Holland	Caltrans Research & Innovation
Arpad Horvath (Day 1 only)	University of California, Berkeley
Hans Ho	Telfer Oil
Robert Karlsson	Swedish National Road and Transport Research Institute, VTI
Asa Lindgren	Swedish Road Administration
Yen Yu Lin	University of Washington
Alex Loijos	Massachusetts Insitute of Technology
Ronnen Levinson (Day 1 only)	Lawrence Berkeley National Laboratory
Amlan Mukherjee	Michigan Technical University
Mike McCarthy	Sonoma Technologies, contract to Caltrans Environmental Analysis
Steve Muench (Day 2 only)	University of Washington
Jeop Meijer (Day 1 by phone)	The Right Environment, Inc.
Alenka Mauko	ZAG, Slovenia
Tom Pyle	Caltrans Pavement Management

Tony Parry	University of Nottingham
Mel Pomerantz	Lawrence Berkeley National Laboratory
Chris Robinette	Granite Construction, Inc.
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