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Pavement Life Cycle Assessment Workshop

University of California Pavement Research Center, Davis and Berkeley

California Department of Transportation

Institute of Transportation Studies, UC Berkeley and UC Davis

With collaboration of: International Society for Asphalt Pavements, Asphalt and the Environment Technical Committee, International Society for Concrete Pavements

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BACKGROUND

The University of California Pavement Research Center (UCPRC, Davis and Berkeley) and the University of California Institute of Transportation Studies (Berkeley and Davis) are working together on establishing common practices for conducting environmental life cycle assessment (LCA) for pavements. Funding for this work is provided by the California Department of Transportation in partnership with the MIRIAM (Models for Rolling Resistance in Road Infrastructure Asset Management Systems, [link to be added]) pooled fund project which is led by the Danish Road Institute (Ministry of Transportation, Road Directorate). This work is being done in 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).

Research products under development as part of this work include:

a. An LCA framework for pavements.
b. A summary of system boundaries and assumptions for the framework, as well as an examination of the pros and cons of alternatives.
c. Assessment of models/data for each phase of the life cycle with regard to project type.
d. Documentation requirements for pavement LCA studies sufficient to permit comparison between studies in terms of completeness, assumptions, system boundaries and data/models.

Desired Outcomes of the Workshop:

1. Review and discussion of documents prepared by the research team for each of the four items (a, b, c, and d) listed above.
2. Brief presentations and discussion of critical issues for pavement LCA where conflicting practices or gaps in knowledge have been identified.
3. Summary of areas of consensus and disagreement with regard to items a, b, c, and d above and documentation of alternative views.

The UCPRC/ITS research team will use the results of the workshop to improve the LCA framework and recommended documentation requirements. The focus of the framework and documentation will be for studies to be performed for California, and later for the MIRIAM project; however, they may serve as guidance documents for pavement LCAs performed in any region. A follow up will likely be required to capture similar information for European studies to be performed as part of the MIRIAM project. The final documents prepared by the research team, after incorporation of the workshop results, were posted for comment and critique by the pavement and LCA communities. The intention of the research team and workshop sponsors is that the results will provide the following benefits:

- Use of appropriate assumptions, system boundaries, models, and data by the research team for the California and MIRIAM studies.
- Better understanding of LCA among pavement LCA practitioners, sponsors, and consumers of pavement LCA information.
- Recommendations for improvement in practice of LCA studies.
- More transparency in the documentation of how pavement LCA studies are performed.

DISCLAIMER

UCPRC PAVEMENT LCA GUIDELINE:

LCA FRAMEWORK AND STANDARD ASSUMPTIONS

Prepared by the Pavement LCA Group at UCPRC (Harvey, Kendall, Lee, Santero, VanDam, Wang)

The *UCPRC Pavement LCA Guideline* includes three documents: LCA Framework and Standard Assumptions, Recommended Models and Data Sources, and a Pavement LCA Checklist.

This document is intended 1) to provide preliminary system definitions for basic elements of pavement life cycle assessment (LCA), and 2) to guide pavement LCA studies. This document attempts to address all the processes involved in a pavement system (except the design period) which may impose impacts to environment. 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 re-constructing 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 comparing warm-mix asphalt and conventional hot-mix asphalt may only include the materials production and construction processes assuming that the systems perform identically in every other way.

It is also important to establish the difference between a pavement and a roadway LCA. The decision to build a roadway is a complex product of mobility and accessibility demands, and balances a host of social, economic, and environmental issues within the decision-making framework *[1]*. From purely an environmental impact perspective, the construction of a new roadway (or expansion of an existing one) will open up new areas of potential impact, such as those spawned by changes to the local and regional economies associated with the transformed corridor. When performing a roadway LCA, it is critical that these indirect (yet highly influential) issues be accounted for in the 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 are indifferent to the type of pavement used on the roadway and can thus be omitted from the scope. Therefore, the scope of a pavement LCA is confined to the issues that are related to the design, materials, construction, and other characteristics of the pavements itself. This delineation is crucial in order to correctly identify what should and should not be included within a pavement LCA. Isolating pavements from roadways allows for a more focused analysis and encourages recommendations to be made that are specific to pavements and their characteristics.

In this document, elements labeled "factors to be included" and those without any explicit indicators are considered significant, and likely to be included within an LCA's system boundary or in a sensitivity analysis. Elements considered potentially trivial or in need of further discussion before they are included in the analyses are labeled "factors requiring discussion before deciding on inclusion."

1 Goal Definition

The International Organization for Standardization (ISO) 14040 standards require that a study's goal be defined at the outset of an LCA. Defining the goal of a pavement LCA includes identifying its purpose and audience. For a pavement LCA, the purpose can be:

- to generate information for decision making for a specific project (project level);
- to characterize a set of discrete projects sufficient to identify the sensitivity to a range of conditions with subsequent policy or decision-making implications by asset managers; or
- to characterize a complete highway network (network level).

This LCA framework provided is intended to guide a project-level study, not a comprehensive pavement network LCA, meaning it is applicable to the first two bullets above.

Project level LCAs can serve as the foundation for analyzing a set of discrete projects. A project level LCA may consider network effects, such as the network effect from the work zone traffic. In project-level LCAs, site-specific and project-specific information should be used (when available) to develop local results. 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, 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 situation, all the processes that have been identified in a pavement system need to be included. 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 the same and omitted must be explicitly and clearly stated in the study's documentation.

2 Functional Unit

The ISO *[2]* defines the *functional unit* as "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 this 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, a typical project length could be between 0.5km and 100km.

2.1.2 Inclusion of shoulder

2.2 Performance requirement

The main purpose of pavements is to carry traffic safely and efficiently. There are several components 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 *[3]* (Topic 612);

2.2.2 Criteria for performance: functional criteria, such as ride quality and safety, and/or related engineering criteria, such as structural capacity and level of distress;

2.2.3 Truck traffic: highway pavements are usually designed to carry a specified volume of truck traffic with defined axle load spectrum and speed characteristics within the functional design life;

2.2.4 Climate: primarily pavement temperatures and rainfall for the project site;

2.2.5 Subgrade: the existing soil or thick imported fill.

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 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. Properly assessing the pavement system over a time horizon presents a major challenge. Some proposed approaches to determine the analysis period include:

3.1 Using 1.2-1.5 times the longest functional design life among all alternatives

3.2 Using minimum next major rehabilitation activity

3.3 Annualizing/amortizing construction events

4 Life Cycle Inventory

Depending on the goal of an LCA study and the specific environmental impacts to be assessed, the environmental input and output to be inventoried may vary. However, it is recommended to track all the available inventories in case of future use. Some commonly used life cycle inventories are listed here.

4.1 Energy consumption

- Feedstock energy must clearly 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 critical 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 (VOC), PM_{10}, $PM_{2.5}$, SO_2, CO, and lead.

- Emissions from potential use of bitumen as a fuel should be considered if the type of LCA approach is consequential. It is not 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 the pavement include pavement design, material production, construction, use, maintenance and rehabilitation, and end-of-life phase. A framework including each phase and some sample materials/processes is shown on page 13.

5.1 Pavement Design

5.1.1 Structural design of each alternative in the analysis, including surface, base, subgrade, shoulder, and drainage.

If the LCA is applied to a rehabilitation activity where the base/subgrade/drainage remains unchanged, these aspects of the structural design can be reasonably left outside the system boundary.

5.2 Material Production

5.2.1 Factors to be included:

5.2.1.1 Material acquisition/production

5.2.1.2 Mixing process of HMA or PCC in plants

5.2.1.3 Feedstock energy of materials that are used as a fuel

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

5.2.2 Factors requiring discussion before deciding on inclusion:

5.2.2.1 Cut-off rule for oil excavation and refining

5.2.2.2 Allocation of impacts during oil refining (asphalt production)

5.2.2.3 Technology improvement over time

5.2.2.4 Equipment manufacturing and capital investments in production facilities

5.2.3 Factors outside the system boundary:

5.2.3.1 Land use/occupation

5.3 Construction, Maintenance and Rehabilitation

5.3.1 Factors to be included:

5.3.1.1 Transport of materials and equipment to site

5.3.1.2 Equipment manufacturing and capital investments attributable to this construction event

5.3.1.3 Equipment use at the site

5.3.1.4 Water transport

5.3.1.5 Water use

5.3.1.6 Energy and emissions used for lighting, if the construction happens at night

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

5.3.1.8 Emission/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
  - Dynamic traffic growth
  - Dynamic vehicle technology/emission

5.3.1.9 Building of roadway lighting system

5.3.1.10 Temporary infrastructure

5.3.2 Factors outside the system boundary:

5.3.2.1 Equipment manufacturing and capital investments.

5.4 Use

5.4.1 Factors to be included:

5.4.1.1 Additional vehicle operation due to pavement deterioration, including fuel economy effect, 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.

5.4.1.2 Heat island effect

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

5.4.1.3 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 can be quantified by CO_2-e offset.

5.4.1.4 Roadway lighting

This generally includes the electricity use.

5.4.1.5 Carbonation

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

5.4.1.6 Water pollution from leachate and runoff

5.4.2 Factors requiring discussion before deciding on inclusion:

5.4.2.1 Long-term asphalt emissions of GHGs and other emissions (asphalt binder aging chemistry).

5.4.2.2 Reduced fuel efficiency and increased emissions due to differences in rolling resistance based on pavement type. Although existing research suggests that pavement type does play a factor in rolling resistance, it is unclear if the information available is sufficient to warrant quantitative inclusion within an LCA.

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

5.5.1 Factors to be included:

5.5.1.1 Recycling imposes a critical problem regarding the allocation of net input/output between the system that generates the "waste" and the system that recycles the "waste." The method of input/output allocation and crediting the virgin material saving regarding using recycled materials need to be reasoned and documented in an LCA practice.

5.5.1.2 Emissions and fuel use from demolition and hauling of debris

5.5.2 Factors requiring discussion before deciding on inclusion:

5.5.2.1 Leachate from landfilling.

5.5.2.2 Leachate from once bound materials now being used as unbound base.

6 Impact Assessment

Impact assessment translates the inventory into meaningful indicators of a product or system's impact on the environment and human health. This is generally achieved by classifying inventory flows into impact categories and characterizing the inventory results through appropriate impact indicators. Some common impact categories include:

6.1 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 source of method used to calculate CO_2-equivalents must be reported in the analysis.

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 effects on human health, or environmental impacts categories, such as ozone depletion potential or acidification potential.

7 Treatment of Uncertainty in LCA

Like other infrastructure systems, a pavement system is a complex, long-lived system. LCA practitioners should be aware that each process during construction or use of the system, and the process of analyzing them, brings inherent uncertainty.

LCI databases elucidate environmental impact of a product or process, but they only represent parts of the real world. For example, a gasoline inventory in an LCI database is produced based on some specific gasoline products available in the market, and may not be representative of the gasoline products available in the market being analyzed. For this reason, LCA practitioners should carefully choose an LCI database based on their project noting that it is common that the LCA practitioner will not find exact matches. In order to reduce this type of discrepancy, LCA practitioners may use LCI data that are similar to the actual material used in the field, or adjust data within a bounded range, or use statistical tools such as a Monte-Carlo simulation if sufficient data exist.

The use phase introduces another kind of uncertainty in the life cycle 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 included, traffic can be the largest contributor to environmental loads. Thus, it should not be omitted unless the study compares two different pavement designs which share every other attribute (a rare situation). Scenario analysis can be used in order to capture uncertainty in the predicting key parameters in the use phase, such as traffic flow and vehicle technology.

Limits in knowledge cause uncertainty. For example, although many researchers have strived to understand the role 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 details can alter the allocation of burdens to a co-product.

Developing detailed models is a possible solution to reduce uncertainties related to lack of knowledge. In addition, scenario analysis of alternate theories or methods can serve as a test of the robustness of study outcomes. A summary of all these uncertainty types and corresponding treatment is shown in Table 1.

Table 1. Summary of treatment of uncertainty in LCA

Types of uncertainty	Recommended treatment
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
Predicting the future - Traffic patterns, growth, and vehicle fleets - Technology advancement	- Scenario & 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 principle factors that affect uncertainty in a pavement LCA study.

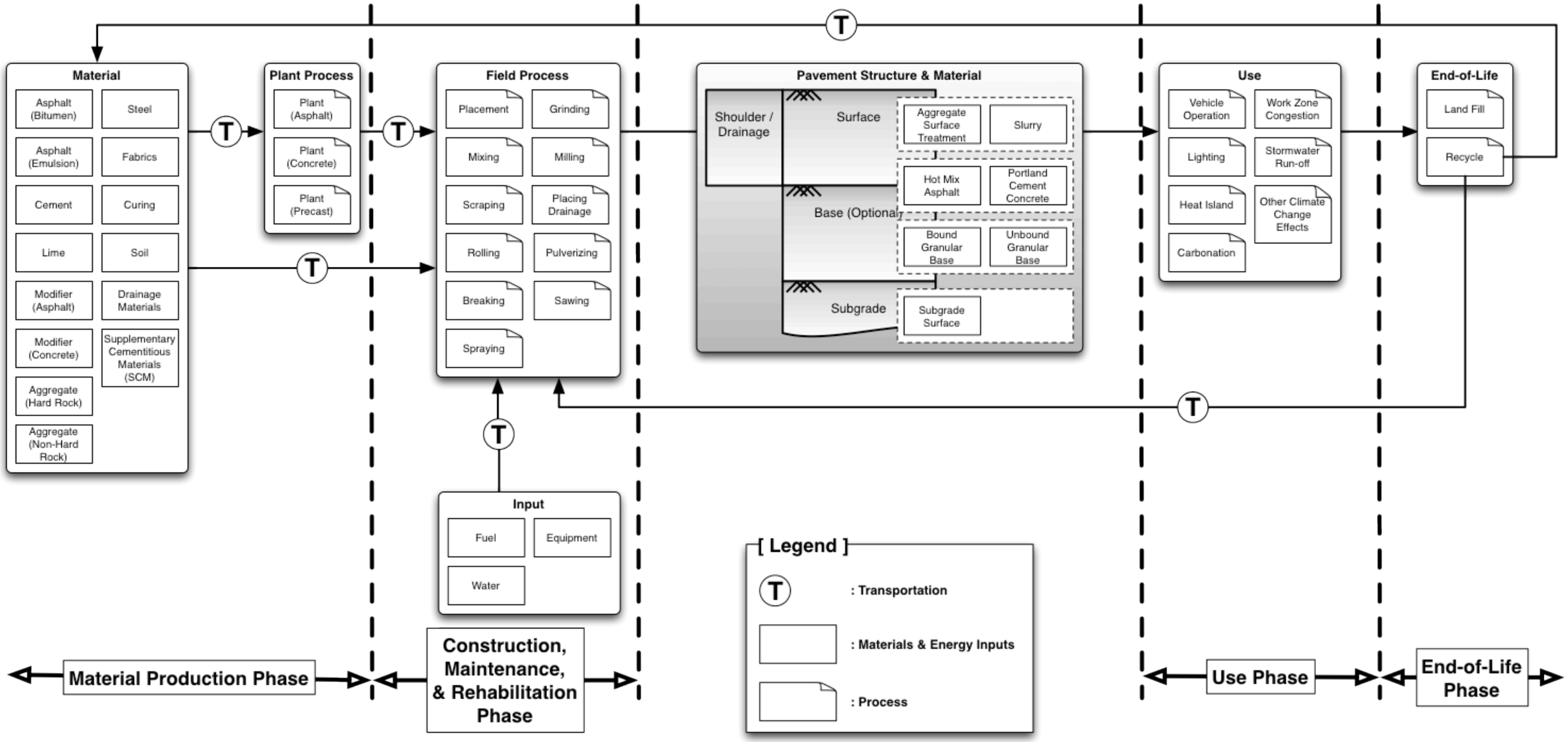
Design and construction processes are influenced by local practice, policy and culture, and a design's performance will be affected by local climate, traffic patterns and growth, and vehicle mix. Unlike consumer products, pavement systems have lifetimes that are decades long, making it difficult to predict how the pavement system will be utilized in the future.

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

- A clear functional unit, system boundary, and goal allowing LCA practitioners to identify sources of uncertainty.
- A transparent study that allows other researchers to improve upon the study as data and theory advance.
- Inclusion of scenario and sensitivity analysis that can test the robustness of LCA modeling outcomes.

PROPOSED FRAMEWORK FOR PAVEMENT LCA[1]

Prepared by the Pavement LCA Group at UCPRC



1 The figure is not intended as a comprehensive or exhaustive list.

UCPRC PAVEMENT LCA GUIDELINE: RECOMMENDED MODELS AND DATA SOURCES (CALIFORNIA OR U.S. FOCUSED)

Prepared by the Pavement LCA Group at UCPRC (Harvey, Kendall, Lee, Santero, VanDam, Wang)

As part of the *UCPRC Pavement LCA Guideline*, this document provides more in-depth discussion of models and life cycle inventory (LCI) data sources for each pavement life cycle phase, and provides examples relevant for California as well as for the U.S. as a whole. Guidelines for choosing the appropriate models and data sets are also provided so that equivalent tools in different regions can be selected. Gaps between current knowledge and analysis requirement are also listed where they have been identified, and these will be the foci for future work.

1. *Example* Materials and Processes Considered in Material Production Phase[2]

1.1. Materials:

Asphalt, asphalt emulsion, asphalt modifiers, portland cement or other hydraulic cement (example: 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 process:

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

1.3. Pavement layer options:

Pavement Layer Options (Bonding and curing materials implied)	Potential Use
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

2 This is not intended as a comprehensive or exhaustive list.

Pavement Layer Options (Bonding and curing materials implied)	Potential Use
Subgrade	Subgrade
Slurry	Surface

1.4. Field Processes:

Transport, placement, rolling, grinding, pulverizing, breaking, mixing, milling, sawing, scraping, spraying, placing drainage

1.5. Since 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 construction event. In a situation where the underlying layer is unclear, it is also important to document the "assumed" underlying structure.

1.6. The cross section of pavement must be defined before a construction activity.

2. *Construction*

Impacts to be considered during the construction stage include fuel use and emissions contributed by both construction equipment and construction-congested traffic. Fuel use must always consider total fuel cycle emissions. Figure 1 shows the recommended analysis procedure.

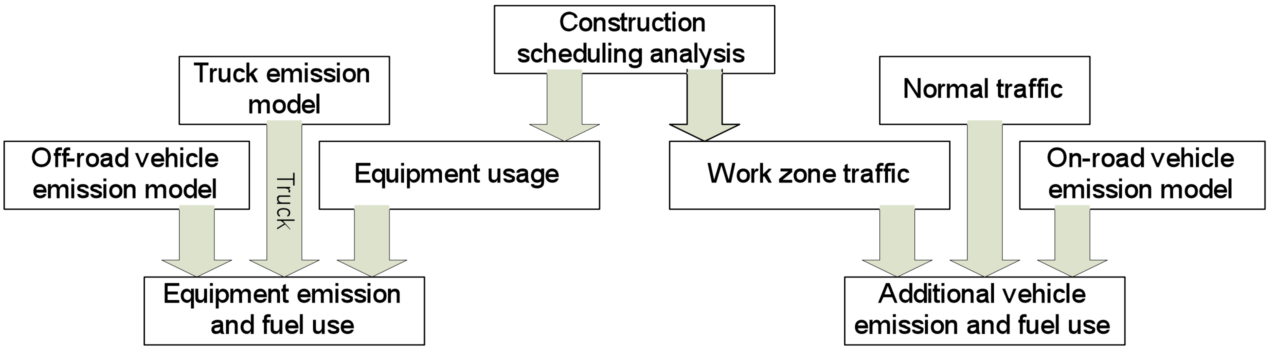


Figure 1. Recommended analysis procedure for construction phase

2.1. *Equipment emissions and fuel use*

The construction schedule, including the pattern of traffic closure and equipment utilization, can be modeled through *CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) [4]*, or a similar model. *CA4PRS* is a software tool that supports the integrated analysis of project alternatives for different pavement designs, construction logistics, and traffic operation options. It provides the activity of construction equipment, which then can be related to the emission factors obtained from an equipment emissions model, such as California's *OFFROAD* model *[5]*, and used to calculate the fuel consumption and emissions of construction equipment. *OFFROAD* is software used to generate emissions inventory data for off-road mobile sources (e.g., a paver or excavator). For states other than California, the US EPA's *NONROAD2005* model *[6]* can be used to calculate air pollutants from off-road equipment. For non-U.S. studies, equivalent models should be used.

Currently, *CA4PRS* can provide the work zone analysis for five types of rehabilitation work, including AC overlay, full-depth AC replacement, mill-and-fill AC rehabilitation, Continuous Reinforced Concrete Pavement (CRCP) rehabilitation, Jointed Plain Concrete Pavement (JPCP) rehabilitation, and PreCast pavement rehabilitation. Lane widening is under development.

Gap:

a) In general, construction processes that are not currently in *CA4PRS* or an equivalent construction schedule model require further investigation. Requesting diaries from similar projects is one option for simulating construction processes that are not already defined in a construction schedule model. This will allow LCA practitioners to model maintenance and rehabilitation options such as whitetopping, slab replacement, and other excluded activities.

2.2. *Additional emissions/fuel use from construction-related traffic*

Construction-related traffic includes the work zone traffic and network effect from construction congestion, such as detours. Currently only the 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 background traffic information, is used as an input for modeling motor vehicle emissions/fuel consumption. Because traffic behavior is a regional-specific issue, special attention needs to be paid to the composition of vehicle fleet and speed distribution. Sensitivity analysis is recommended regarding the changes in fleet composition, speed distributions, and 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) *[7]*. *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 US EPA's *MOVES* (Motor Vehicle Emission Simulator) model *[8]* may be used for on-road mobile source emissions. The current version of *MOVES* is ver. 2010.

Gap:

a) *EMFAC* requires a speed spectrum to calculate the 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* and *MOVES* only consider a static traffic speed; however, acceleration and deceleration of vehicles in congestion contributes to additional fuel consumption. This shortcoming would lead to an underestimation of fuel consumption in stop-and-go congestion.

c) The network effect from construction congestion could also lead to additional emissions and fuel use. This problem needs further investigation.

3. *Use*

3.1. *Additional vehicle operation*

Currently, only the fuel consumption in vehicle operation is proposed for analysis. The deterioration of pavements increases rolling resistance, and thus lowers fuel economy and increases the energy that traffic consumes. Pavement condition can be modeled and estimated through pavement performance modeling, and rolling resistance can be a parameter in estimating the fuel economy. In this way, additional fuel consumption due to deteriorated pavement can be evaluated through the change of pavement condition over the long run. One tool for evaluating this relationship is *HDM-4* (Highway Design and Maintenance Standards Model - ver.4), a model developed by PIARC (World Road Association) to conduct cost analysis for the maintenance and rehabilitation of roads *[9]*. It 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. Also, since traffic behavior is included here, the fleet composition, speed distribution, and new vehicle technologies need to be treated similarly as construction-related traffic.

Gap:

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) Similarly as in 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 the deterioration of pavement condition need to be determined.

3.2. *Urban heat island*

Two mechanisms have been identified as affecting 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 increased use of air conditioning or greater energy needed for air conditioners to work because they intake warmer air) or energy offset in buildings or vehicles.

Nearly all pavements are impermeable, thus cutting off the soil beneath from the air, and reducing the evaporation of water from the soil into the near surface atmosphere. A new type of pavement, referred to as fully permeable pavement, where subgrade has contact with air through pavement (sometimes referred to as pervious pavements or porous pavements), may have less heat island effect than ordinary pavements because of evaporative cooling due to its high porosity and ability to pass evaporated water from the ground into the air.

The Heat Island Group at Lawrence Berkeley National Laboratory has conducted many studies on this topic and developed a semi-quantitative relationship which characterizes air and pavement temperatures *[10-11]*. Future work would focus on how to convert the air temperature change to the related system-wide energy consumption change.

Since the current understanding of this effect from pavement is still limited and uncertainty of the results is very high, when the urban hear island effect is considered in an LCA study, the following work is recommended:

- Albedo is not the only factor that affects the ambient temperature. Surface impermeability is also an important factor that will be analyzed, and there are other micro-climate related factors that may be as important as or more important than albedo.
- Include pavement temperature and reflectance effects as an option for pavement LCA in a sensitivity analysis.
- If it is considered, the effects must be specific to the location considered in the study, 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, so more than just the albedo at initial construction needs to be considered.

Gap:

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

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

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

3.3. *Non-GHG climate change effect*

Currently only radiative forcing from albedo is considered.

High albedo contributes to the global cooling by reflecting a portion of the incoming radiation back to space, thus producing a negative radiative forcing. The Heat Island Group at Lawrence Berkeley National

Laboratory has also made an attempt to quantify the relationship between changes in albedo and offset in CO_2 equivalents *[12]*.

Gap:

a) The study modeling the albedo-radiative forcing relationship at the Heat Island Group of the Lawrence Berkeley National Laboratory 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) *[13],* a software program developed by the Federal EPA to model the transport and fate of waste constituents through subsurface soils and groundwater to a well.

Gap:

a) Identify an equivalent model to *IWEM* for tracking the transport of pollutants to *surface water*. The pollution in surface water is often a more critical environmental compartment for many run-off events.

b) Different pavement designs have different effects on depositing and transporting pollutants in water and changing the water temperature. How to characterize the differences in pollutant movement among different pavement systems needs further investigation.

4. End-of-Life of Materials

When a material reaches its end of life, there are typically two options: recycle it or send 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. The burden of producing the original system and virgin materials, as well as the burden of the recycling process must be allocated between the original pavement system and future pavements that use the bulk of the same material and substructure.

Häkkinen and Mäkelä *[14]* considered allocation of recycled materials, and assumed that each construction event is only responsible for the materials they use. This implies that the first construction event takes all of the environmental burdens from using virgin material, and the following construction will take the environmental burdens only from processing and transporting recycled materials. The environmental impact of waste was not considered in this report.

Recognizing that recycled material systems benefit from the original production of materials or systems, Ekvall *[15]* proposed a 50/50 method which allocates the burden of virgin material production and final end-of-life waste half to the first construction event and half to the final construction event. The environmental burdens of recycled materials are allocated half to the preceding construction and half to the following construction.

Among other potential obstacles to implementing Ekvall's method, it requires that the LCA practitioner predict the number of times a material is recycled and the fate of those recycled materials. Thus, a method that can accommodate the modeling of a specific construction event or site is required. At a minimum, 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.

4.2. Landfilling

Impacts from landfilling include the burdens of transporting waste to the landfill site and leaching from waste once it is deposited in the landfill. 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 the site of C&D landfills and found less than one percent of sites showed any water quality impacts *[13, 16]*. Therefore, the impacts from waste transport will likely be the dominant effect of the landfilling process.

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UCPRC PAVEMENT LCA GUIDELINE:

PAVEMENT LCA CHECKLIST

Prepared by the Pavement LCA Group at UCPRC (Harvey, Kendall, Lee, Santero, VanDam, Wang)

This 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 in the basic elements of LCA (such as system boundary or data source) among different studies. A simpler and more graphical version of this list is being prepared for use by LCA reviewers and will be included with a future version of this document.

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" 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: __________years analysis period:

1.4 Life Cycle Inventory

1.4.1 Primary energy: ☐

Clearly distinguish feedstock energy 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 Life Cycle Phases and Their System Boundary

1.5.1 Pavement design (for each system)

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

1.5.2 Material production

1.5.2.1 *Raw material*

Material production: ☐

Feedstock energy: ☐

Transport of materials to site: ☐

1.5.2.2 *Engineered material*

Mixing in plant (HMA or PCC): ☐

Transport from/to plant: ☐

Transport of recycled material: ☐

1.5.3 Construction

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

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:	☐		
Sensitivity analysis:	☐		

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

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 Climate change

Global warming potential (GWP): ☐

Source : ☐ IPCC TAR ☐ IPCC AR4 ☐ Other ______

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

1.6.2 Other

Other impact categories: _______________, _______________, _______________, _______________, _______________, _______________

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]: ___________

Type: ☐ LCI Tool ☐ LCI Study

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:	___________