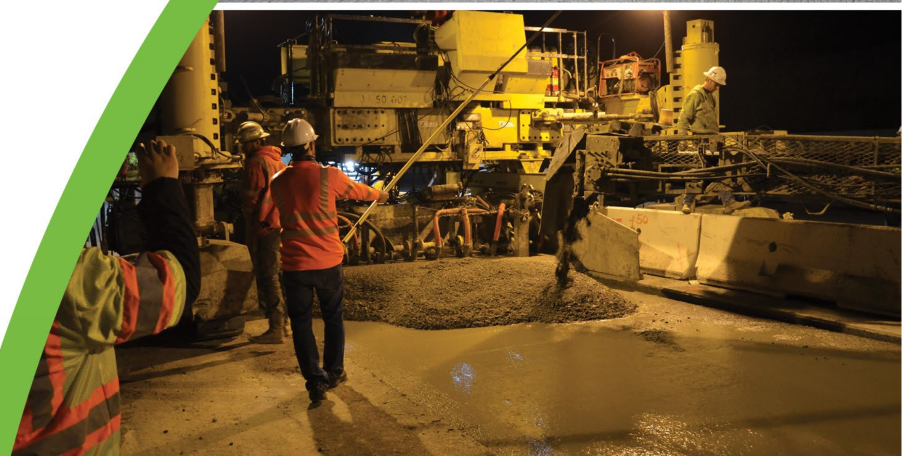
LCA Pave: A Tool to Assess Environmental Impacts of Pavement Material and Design Decisions

Underlying Methodology and Assumptions



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16. Abstract

This report documents the underlying basis and foundation used in the development of LCA Pave, a tool for the assessment of environmental impacts of pavement material and design decisions. The purpose of this document is to describe the general methodology employed, the key assumptions made, and the type and sources of data used in the tool, while also disclosing its overall boundaries and limitations and the type of analyses that it can support.

The report provides details on the following topics:

1. Goal and scope of the tool.
2. Procedures used for inventory analysis, impact assessment, and interpretation.
3. Data quality assessment.
4. Incorporating environmental product declarations (EPD) into the tool.
5. Allocation procedures.
6. Assumptions, limitations, and data gaps.

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CHAPTER 1. INTRODUCTION

1.0 BACKGROUND

Life-cycle assessment (LCA) is a technique that can be used to evaluate the environmental burden of a product or process by examining all of the inputs and outputs over the life cycle, from raw material production to end of life. This systematic approach identifies where the most relevant impacts occur and where the most significant improvements can be made while identifying potential trade-offs[1]. It gives agencies the ability to investigate areas where they can improve.

> Sustainability can be described as being made up of the three components—environmental, social, and economic needs—that collectively are referred to as the "triple-bottom line." According to FHWA, sustainability refers to system characteristics that encompass a pavement's ability to (Van Dam et al. 2015):
>
> - Achieve the engineering goals for which it was constructed.
> - Preserve and (ideally) restore surrounding ecosystem.
> - Use financial, human, and environmental resources efficiently.
> - Meet basic human needs such as health, safety, equity, employment, comfort, and happiness.

Although some LCA tools exist, the Federal Highway Administration (FHWA) sought the transparent development of an LCA tool for pavements, in collaboration with key stakeholders, that made use of publicly available data. The resultant tool, *LCA Pave*, can be used to support transportation agencies in conducting LCA and can accept data from industries available Environmental Product Declarations (EPDs). The tool is also complementary to the FHWA's Infrastructure Carbon Estimator (ICE) tool which was originally designed by FHWA for pre-engineering analysis of greenhouse gas (GHG) emissions for infrastructure construction and maintenance. The tool was subsequently improved through a pooled fund initiative and can be found at: https://www.fhwa.dot.gov/environment/sustainability/energy/tools/carbon_estimator/index.cfm

LCA Pave is project-level tool and does not relate to or interface with pavement management systems. It is also not intended to be used in pavement type decisions (i.e. asphalt vs. concrete).

The LCA Pave tool is intended to be used as a training and informational product only and for voluntary use by agencies and individuals with an understanding of fundamental LCA principles. Its use is not required by Federal statute or regulation. The tool can be accessed at: https://www.fhwa.dot.gov/pavement/lcatool

1.1 DOCUMENT PURPOSE

The purpose of this document is to provide transparency about the background and development of the tool and to disclose its boundaries, limitations and the type of analyses that it can support in accordance with ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) standards (which are voluntary and not required by Federal statute or regulation). The FHWA *Pavement Life-Cycle Assessment Framework* (Harvey et al. 2016) ("framework document") was used as the basis for the development of the tool, as documented in this report. The practices identified in the framework document were followed unless there was a sound and logical reason for deviation.

[1] Pavement Life Cycle Assessment Framework - https://www.fhwa.dot.gov/pavement/sustainability/hif16014.pdf

A companion user manual from FHWA describes the tool features and functionality (Ram et al. 2021).

1.2 TARGET AUDIENCE

Transportation agencies are the primary audience for the tool, with the predominant users being the pavement and material engineers.

1.3 INFORMAL OPEN REVIEW

To help ensure the validity of the tool and its underlying assumptions, the development team engaged with key stakeholders throughout the development process. The tool and accompanying documentation were developed with FHWA and stakeholder input, including the Sustainable Pavement Technical Working Group (SPTWG). Furthermore, several users from State DOTs, referred to as the Pavement Life-Cycle Thinking (PLCT) Task Group, provided input regarding all product deliverables and participated in a focused beta testing event along with members of the SPTWG. The stakeholders involved in the tool development effort are shown in figure 1-1.

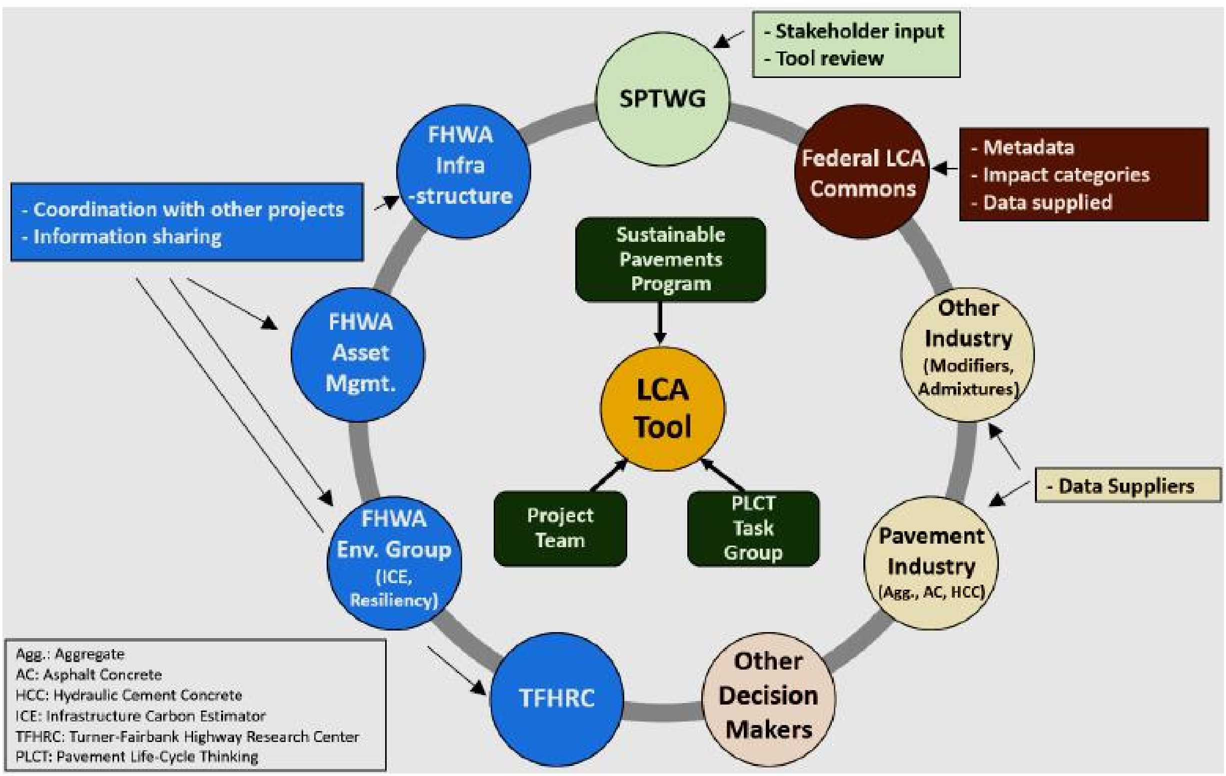

Figure 1-1. Stakeholders involved in the input and review of the tool and documentation.

1.4 RELATIONSHIP WITH PARALLEL FHWA PROJECT

A parallel FHWA study provided technical support in the development of the tool, with results documented in a paper by Bhat, Mukherjee, and Meijer (2021). That paper conveys the methodology and approach followed in this report and in the tool, particularly in the development and application of the data quality pedigree matrix that has been applied to the data used in the tool. In addition, the results from the background data work mentioned in the paper are used for equipment, transportation, waste, fuels and electricity within the tool. Other topics covered in the paper of relevance to this study include (Bhat, Mukherjee, and Meijer 2021):

- Mapping unit and product system processes for pavement LCA.
- Identifying common publicly available background datasets to aid consistency in pavement LCA.
- Developing methods to assess the quality of the background and foreground datasets used in pavement LCA.

In addition, a previously published FHWA report provided suggested strategies to help ensure the integrity of using LCA-based instruments in business processes (Mukherjee, Bhat, and Harvey 2020).

1.5 REPORT ORGANIZATION

This report consists of six chapters (including this introductory chapter) and two appendixes.

- **Chapter 2: Goal and Scope of Tool**. This chapter presents the goal and scope of the LCA tool, describing the functional unit, boundaries of tool, and the types of analyses that can be performed.
- **Chapter 3: Tool Data**. This chapter describes the data sources that are used in the tool, and the results of the data quality assessment. In addition, the potential use of EPDs as a secondary data source is discussed.
- **Chapter 4: Impact Assessment Methodology**. This chapter presents the impact categories that are included in the tool, and how they are considered in the analyses.
- **Chapter 5: Interpretation and Reporting**. This chapter provides information on how the results from the tool are reported and how they can be used in the interpretation of the results to address the goal of the LCA study.
- **Chapter 6: Summary**. This chapter provides an overall summary of the foundational work for the tool development efforts (including assumptions, limitations, and data gaps).
- **Appendix A: Glossary**. List of terms used in this report and the tool.
- **Appendix B: Tool Database**. Details on the library database items included in the tool.

CHAPTER 2. GOAL AND SCOPE OF THE TOOL

This chapter presents the goal and scope of the LCA tool, describing the functional unit, boundaries of tool, and the types of analyses that can be performed.

2.0 GOAL

The tool's goal is to aid agencies to assess, quantify, benchmark, and communicate the environmental impacts for the following *use-cases:*

- *Use Case #1:* Comparisons supporting the evaluation of alternative pavement materials, pavement structures, pavement treatments, materials transportation, recycling, and construction approaches for a given project.
- *Use Case #2:* Environmental impacts from pavement materials and structural designs that are not necessarily a complete project, or actually applied.
- *Use Case #3:* Comparisons of alternative conceptual decisions and pavement designs during project-level design studies.

The tool considers the impacts associated with the material usage, construction, maintenance and rehabilitation, and end-of-life stages of the pavement life cycle, but does not include any impacts related to the use stage.[2]

This tool is intended for project-level analysis only.

The tool calculates environmental impacts and produces an output report template that can be customized by an agency to present a summary of the project information and the overall results produced by the tool to facilitate interpretation and communication.

Agencies could use the tool in this progression:

- Tool adoption and improvement
  - Agencies can begin performing initial studies using the tool with the initial inventory data in the tool, which is supplemented with available agency project and performance information. This can be aligned with information and level of detail about project life cycles similar to what is used in routine Life-Cycle Cost Analysis (LCCA); in doing so, agencies can populate the tool with agency-specific data. The intention of the tool is that after some initial experience a user may do a project-level LCA study in about 4 to 8 hours for each analysis alternative, similar to LCCA (Rangelov et al. 2020).
  - Agencies can customize the data in the tool using more regional applicable and complete data and develop their own standardized practices for use-case LCA studies over several years of use; the continued improvement of the tool and its adoption in practice depends on how focused it is on agency needs and context.
- Tool uses

[2] The use stage includes environmental impacts associated with vehicles using the road; these use-stage impacts can be significantly higher than those impacts associated with just the pavement materials and pavement construction stages (Van Dam et al. 2015).

- Initially, the tool can be used for educational purposes to help highway agencies familiarize themselves with LCA concepts.
- Agencies and individuals more familiar with LCA concepts can use the tool to identify the most important contributors to differences in the LCA results from the tool analyses and eventually inform development of agency policies and specifications affecting pavement sustainability.
- With accumulation of specific, relevant and complete data over time, tool use could be expanded to a wider range of agency pavement decisions in the future.

The tool complements existing engineering and economic considerations and, as such, provides information about environmental considerations that can lead to more informed decisions; it may have particular relevance when decisions are to be made on "what to build" as expressed in the above-mentioned *Use Case #1*. The tool does not provide complete information regarding environmental considerations because of current data limitations and the lack of consensus related to use stage impacts.

2.1 SCOPE

2.1.1 General

The general scope was:

- Include an initial set of pavement material technologies.
- Focus on project-level analysis.
- Include the materials and construction life-cycle stages in a full analysis period, including the sequence of materials and construction activities throughout the life cycle. This analysis also includes transportation and equipment mobilization and use for activities including construction, maintenance, and rehabilitation.
- Use publicly available national averages for default material, process, and activity data.
- Allow the user to add, store, and call upon agency specific data the tool's library.
- Allow the user to add EPDs for pavement materials.

The tool can be used to conduct a nearly complete life-cycle assessment of the impact of materials, construction processes, and related transportation activities for various pavement mixtures and pavement designs used in all aspects of pavement work (i.e., new construction, reconstruction, rehabilitation, and maintenance and preservation). However, importantly, the tool does not include the use stage, except for the placement and timing of future rehabilitation and preservation treatments. This leaves out the effects of work zones[3] (e.g., work zone speed changes, travel delay, and diversions), pavement-vehicle interaction and related fuel use and emissions, ice and snow management, storm water runoff, heat island effects, and carbonation. The tool will accommodate the addition of these modules as more information becomes available in the future.

Life-cycle stages considered by the tool are shown in figure 2-1. Additional information on each pavement life-cycle stage is available from FHWA (Van Dam et. al. 2015).

[3] This is a deviation from the generally used approach for LCCA.

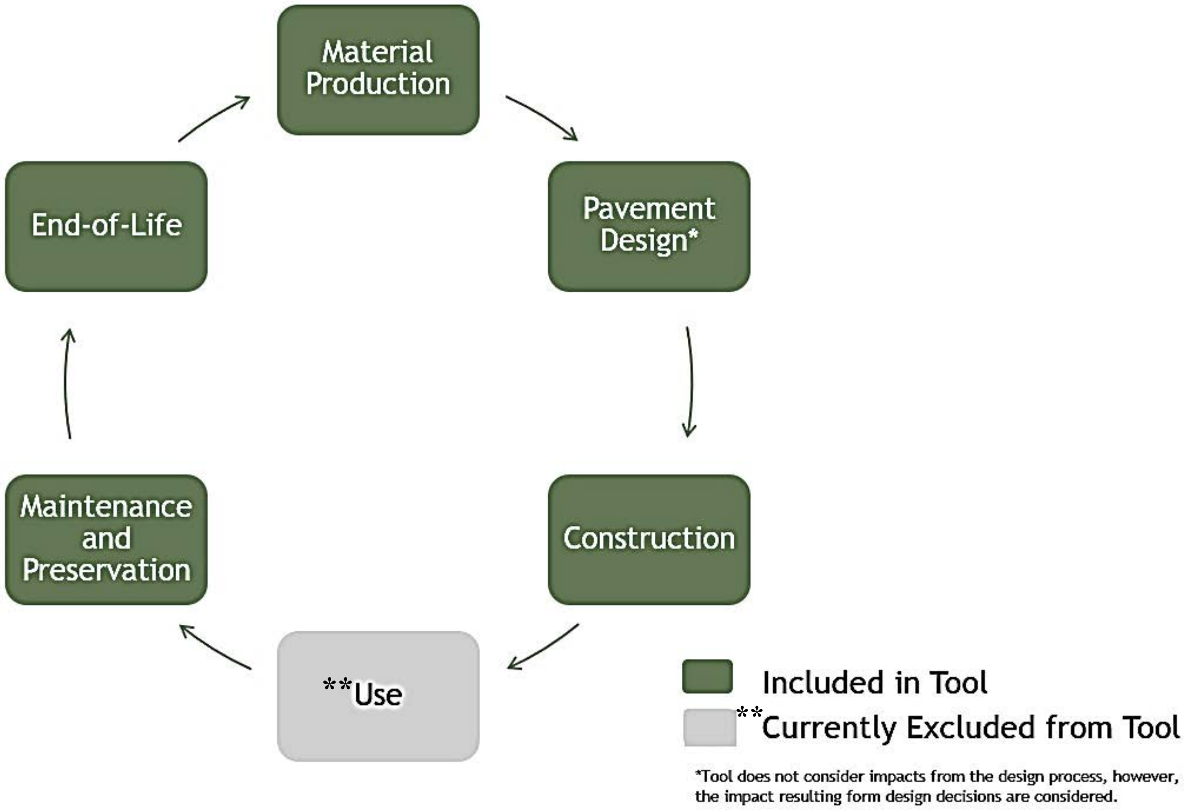

Figure 2-1. Life-cycle stages considered in the tool.

Another user choice is whether to include all pavement layers. For example, if two alternatives for resurfacing are being considered, the layers that are not being touched by either alternative may be excluded, and the slopes of fill sections may be included or left out. The user could decide to model a partial life cycle, for example, cradle-to-built. Users select the pavement system that can satisfy their analysis goals for the use-case of interest.

The tool excludes the consideration of equipment manufacturing and capital investments in construction-related production facilities and follows an attributional approach[4] and not a consequential approach.[5] Table 2-1 shows the scope of the tool in terms of modules and life-cycle stages in relation to terminology used by FHWA (Van Dam et. al. 2015) and by the

[4] Many pavement LCA studies are attributional, meaning they are based on estimating the "flows and potential environmental impacts of a specific product system typically as an account of the history of the product" (ISO 2006b). This may be useful in understanding the impacts of a pavement project or network or for comparing alternatives for a pavement project (i.e., the choice of pavement type) that will not change the systems that they interact with, such as inducing price changes or consumer behavior changes.

[5] Consequential LCAs assess the environmental impacts of changes to an evaluated system. This can be useful in evaluating system-wide impacts. Additionally, consequential LCA can be useful for infrastructure and planning studies that evaluate decisions that have longer-term and more far-reaching consequences not considered in attributional studies.

International Organization for Standardization (ISO) for EPDs (ISO 2006c; ISO 2017) in terms of modules and life-cycle stages. This table is included to assist the user in the alignment of the pavement design process and the codified language, especially since the tool is aimed at agencies, but also allows for the use of EPDs.

Table 2-1. ISO modules and life-cycle phases.

Pavement Life-Cycle Stage (from FHWA, Van Dam et al. 2015)	Pavement Life-Cycle in the Tool	ISO 21930 Modules	ISO 21930 Life-Cycle Stages
Pavement design	Initial construction	Not a life cycle module	Production
Material production	Initial construction	A1: Extraction and Upstream production A2: Transport to factory A3: Manufacturing	Production
Construction	Initial construction	A4: Transport to site	Construction
Construction	Initial construction	A5: Installation	Construction
Use	*(not included)*	B6: Energy use	Use
Use	*(not included)*	B7: Water use	Use
Maintenance and preservation	Preservation	B3: Repair	Use
Maintenance and preservation	Maintenance	B2: Maintenance	Use
Maintenance and preservation	Rehabilitation	B4: Replacement B5: Refurbishment	Use
End -of-life	Removal	C1: Deconstruction C2: Transport C3: Waste processing C4: Disposal of waste	End-of-life
End -of-life	Reconstruction	*(not included)*	*(not included)*
End -of-life	*(not included)*	D: Potential net benefits from future reuse, recycling and/or energy recovery beyond the system boundary	*(not included)*

2.1.2 Tool Libraries

Within the tool a "pavement" is an object with varying numbers of hard surfaced lanes, which may include an inner and outer shoulder, and can all have several layers including a base and subgrade. Users can select the number of lanes, shoulders, and layers that are part of the analysis. Or, users can identify the length and width of the paved area instead, which allows for the accommodation of a rectangular surface area such as a parking lot. The parameters of the user-identified pavement object are added to the output reports.

Generally, a pavement is surfaced with various types of asphalt concrete (AC) or hydraulic cement concrete (HCC). For the purposes of this document, all surfaces constructed with asphalt materials are generically referred to as “asphalt” pavements; all surfaces constructed with HCC are generically referred to as “concrete” pavements. The tool does not impose any limitations on the user regarding layer sequencing of materials or their dimensions.

The tool scope excludes roadway elements such as lighting, traffic management devices, landscaping, structures (bridges, overpasses, culverts), safety devices (guard rails, K-rails, median dividers), drainage and stormwater handling devices that are not pavement (curbs, gutters, inlets, drainage pipes, filters), striping, signage, and message boards.

The libraries included in the tool are described in the following sections.

2.1.2.1 Materials

Material data are gathered from publicly available data sources and aim to represent the best available data for each item. This can include industry data published as EPDs or literature data. The tool aims to provide data that can be considered default data or initial LCI dataset for representative materials and material technologies used in the United States. Alternative materials data for different regions are not included in the tool. Users should include more regionally specific data. The tool has material data for asphalt, concrete, and other composite materials, and offers users the functionality to include mix design proportions from their own mix designs. EPDs can be included on both levels, providing users with the flexibility to include EPD data for mix designs or to include EPD data for mix design component materials such as a cement or asphalt binder, an aggregate source, or an additive. However, the tool does not function as an “EPD generator” on either the material level or the mix design level.[6] More information on EPDs is available in a separate Tech Brief from FHWA (Harvey et al. 2020).

Appendix B includes a detailed overview of the data approach for materials.

2.1.2.2 Equipment

Equipment is used in many material pavement technologies and treatments. Construction activities are modeled in terms of equipment type and equipment use hours based on the U.S. Environmental Protection Agency (EPA) MOtor Vehicle Emission Simulator (MOVES) model (EPA 2014). MOVES is a state-of-the-science emission modeling system that estimates emissions for mobile sources at the national, county, and project level. Appendix B includes a detailed overview of the data approach for equipment.

2.1.2.3 Waste

The waste library describes the impacts associated with destinations and expected uses or disposition of generic types of waste, including pavement demolition (see figure 2-2). Some waste processing data (e.g., for the processing of reclaimed asphalt pavement) are taken from publicly available literature, while most comes from the U.S. Environmental Protection Agency (Niblick et al. 2020). Appendix B includes a detailed overview of the data approach for waste.

[6] EPDs typically are used after a study or tool has been approved by a Program Operator using a dedicated Product Category Rules (PCR) document (note: A PCR document presents standards and guidelines used in developing and reporting EPDs; they are not required by law or Federal regulation). Since no PCR documents exist for pavement LCA in general, this tool cannot generate Pavement EPDs. This tool has not been reviewed and accepted by existing Program Operators for specific materials that can be modeled in the tool, primarily because of the need for better harmonization between the different Program Operators.

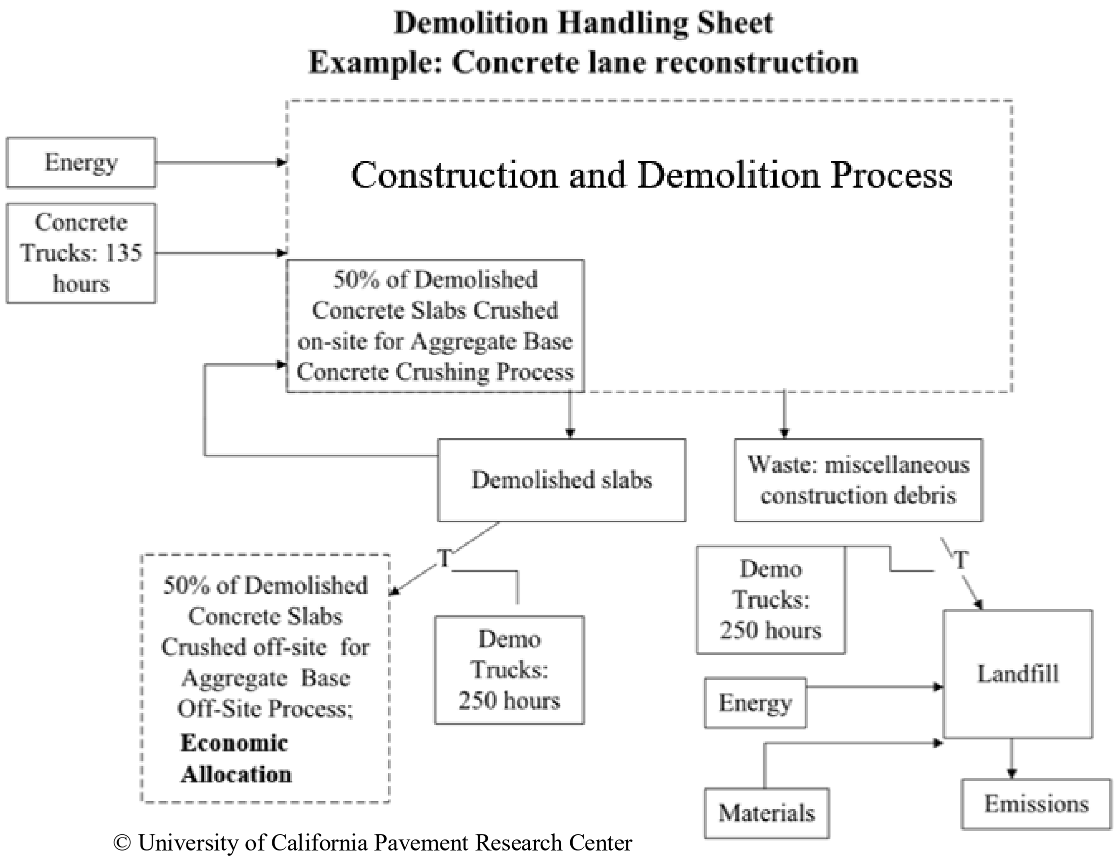

Figure 2-2. Illustration of construction and waste treatment data.

2.1.2.4 Transport

Transportation is modeled in terms of transportation type and distance based on national averages from National Renewable Energy Laboratory (NREL) data published in the U.S. Life Cycle Inventory (USLCI) database made available through the online Open Source LCA platform OpenLCA. NREL is a national laboratory of the U.S. Department of Energy. Appendix B includes a detailed overview of the data approach for transportation.

2.1.2.5 Fuels

Fuels data are modeled using national averages from NREL data. Appendix B includes a detailed overview of the data approach for fuels. Fuels data are currently included in the tool materials library. Future versions of the tool may have a dedicated library for fuels.

2.1.2.6 Electricity

Regional electricity data are provided using National Energy Technology Laboratory (NETL) data from the NETL Appendix B includes a detailed overview of the data approach for electricity. Electricity data are currently included in the tool materials library. Future versions of the tool may have a dedicated library for electricity.

2.1.2.5 Mix Design

Users can develop a database with agency specific mix designs that include materials and plant operations or add EPD-based mix data that typically includes both. Some publicly available EPD-based mix data are included in the default database as an example of how this type of EPD data can be used, but it is not an exhaustive list of available EPD mix data. There are no Federal statutes or regulations on the use of EPDs.

2.1.2.6 Activity

Users can identify agency-specific activities as part of the pavement life cycle. The tool's default database does not include typical activities as these can vary by agency; consequently, agencies can develop specific activities representative of their practices and store them in the database for future uses. This allows for expedited future modeling as many activities, or many activity details, are the same for similar projects within the same agency. Activities can include items from any of the other libraries mentioned above.

2.2 TARGET AUDIENCE

As noted previously, transportation agencies are the primary audience for the tool, with the primary users the pavement and material engineers. These users should set the desired analyses within the tool, which identifies the inputs that are needed for these analyses. User-identified inputs include the choice of use-case, pavement design, material composition, dimensions of the project, the performance of the materials and structures, transportation distances and modes, and the sequencing and choice of treatments. These user-specified inputs are key to a proper analysis and to ensure the integrity of the LCA-based information.

2.3 FUNCTIONAL UNIT

The functional unit describes what is being studied by setting the physical unit and quantified performance that is to be met over a period of time.

Specific information about the functional unit is established by users when the design alternatives are modeled within the tool. Possible information includes:

- **Alternative scope and size**: pavement section facilities (mainline, shoulders, ramps, etc.) included in the analysis, in terms of number of lanes, length and width of the facility. Users can model different layers within each of these pavement types. The dimensions are only used for reporting and for normalization of the results per length or area, as the tool does not perform material quantity calculations.
- **Location**: area (or a section of it) maintained by the agency.
- **Description of the functional performance**: the agency's specifications.
- **Analysis period**: the modeled service period.

Users can describe the functional unit when a new session is started and more details about the scope and size when the alternatives are established. The results can be expressed in the following units: entire project (as established by the user), per lane mile, per lane mile per year, per sq. ft., or per sq. ft. per year. The tool cannot assess the validity of the analysis because the users control the description of the functional unit.

The tool assumes that for comparisons the functional unit for each alternative is the same (or "homogenous"). The data input for each alternative should add up to the same project scope, location, functional performance and analysis period (exceptions for having the same analysis period are discussed below). This means that comparative analyses can only be done for projects or projects with aggregation of subsections that have the same scope; comparison of projects or projects consisting of sub-sections with different functional units is not possible with the tool.

Whenever the goal of the study is the comparison of alternatives, the functional units of the alternatives must be described so that they can be compared without bias. Examples include using the same design life[7] for a pavement lane, which could be expressed in terms of the equivalent traffic loadings to the first major rehabilitation or reconstruction.

2.4 ANALYSIS PERIOD

Each alternative can be modeled for a certain period of performance referred to as the analysis period. The analysis period should be long enough to capture the next rehabilitation or other major event whose timing is influenced by the current decision (Harvey et al. 2016). Detailed information on selecting the appropriate analysis period is available in Sections 3.2.2 and 3.3.2 of the FHWA *LCA Framework Document*.

2.5 ALLOCATION PROCEDURES

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 (ISO 2006b). ISO recommends that allocation be avoided wherever possible and when allocation is unavoidable, it is important that the input or output flows be partitioned in a practical way that reflects their actual relationships with the product systems. ISO is not a Federal requirement. The general principles and examples are shown in table 2-2.

User interaction with allocation is typically restricted to two situations. The first is when a recycled material is being used as a material input for an activity or mix design. This would be modeled in the tool using the approach in the table above under "Use of recycled or secondary materials." The material impacts include all the processing (after demolition and transport to the processing site) to reuse the material in the new application, as well as subsequent transportation from the processing site, if applicable. The second situation would be the removal of materials for recycling. This would be modeled in the tool using the approach in table 2-2 under "Output of material to be recycled or products to be reused." The waste treatment impacts after removal include handling and transport to the waste treatment site for processing up to the point when the material gets an economic value ("end-of-waste"). All processing and handling after this point is part of the use of recycled or secondary materials.

[7] Design life: Time from original construction to a terminal condition state when the pavement is in need of a major rehabilitation or a reconstruction activity to restore the structural and functional performance.

Table 2-2. Overarching allocation principles.

Item	Allocation Principles
Multi-output processes	When assigning flows to multiple products that come from the same unit process, the intent of why the process takes place is followed. If no suitable physical or functional relationship can be established, an economic assignment of process data to the products is applied. *For example, when fly ash and electricity are produced at a coal fired power plant, the economic value is used to assign the plant production flow data for the complete process to each of these co-products, which in this case is negligible for the fly ash due to its low economic value compared to the value of the electricity that is produced. Any processing following the capture of the fly ash is part of the material use of the fly ash.*
Multi-input processes	When various products are processed together within an individual process, e.g. in a landfill site, allocation is performed based on a physical classification of the material flows. *For example, when a material is sent to landfill, the emissions that can be separately associated with concrete, asphalt, steel etc. are considered.*
Use of recycled or secondary materials	Recycled or secondary materials are treated as "free" of burden from the previous use but do include the processing and handling it takes to be able to utilize these materials. *For example, when using RAP as a material in a mix design, the processing and handling at the RAP processing site, like crushing , screening, sorting, stockpiling and loading for transport, as well as any subsequent transportation, are associated with the recycled material in the current use, but the production of asphalt for the previous use as well as the milling at the end of the previous use and transportation of the RAP to the plant are not.*
Output of material to be recycled or products to be reused.	Handling and transportation to the treatment site is included. Any necessary processing is assigned to the use of recycled or secondary materials or the reuse of products. Modeling is included to what is referred to as the "end-of-waste" state in the EN15804 standard on EPDs (CEN 2013). A material has reached the end-of-waste state when it complies with all the following criteria: - the recovered material, product or construction element is commonly used for specific purposes. - a market or demand, identified e.g. by a positive economic value, exists for such a recovered material, product or construction element. - the recovered material, product or construction element fulfills the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products. - the use of the recovered material, product or construction element does not lead to overall adverse environmental or human health impacts. *For example, if a material is demolished at the construction site (demolition needs to be modeled using equipment in the tool) and transported to the waste treatment site for processing (transportation needs to be modeled in the tool), users should stop modeling when the materials gets an economic value ("end-of-waste"). All processing and handling after this point is part of the use of recycled or secondary materials (see line item above).*

2.6 TOOL STRUCTURE

The items stored in the libraries (discussed under Section 2.1.2) can be used to model the desired use case in the tool. The structure is presented in figure 2-3. All library items are referred to as "processes" that can be used to model activities, which are combinations of one more processes. Activities over time can be used to model life-cycle stages. Activities are organized by pavement element, such as mainline or shoulder. Users can model several alternatives within each session. Examples on using items from the tool libraries to develop building blocks for LCA is discussed in the *User Manual* (Ram et al. 2021).

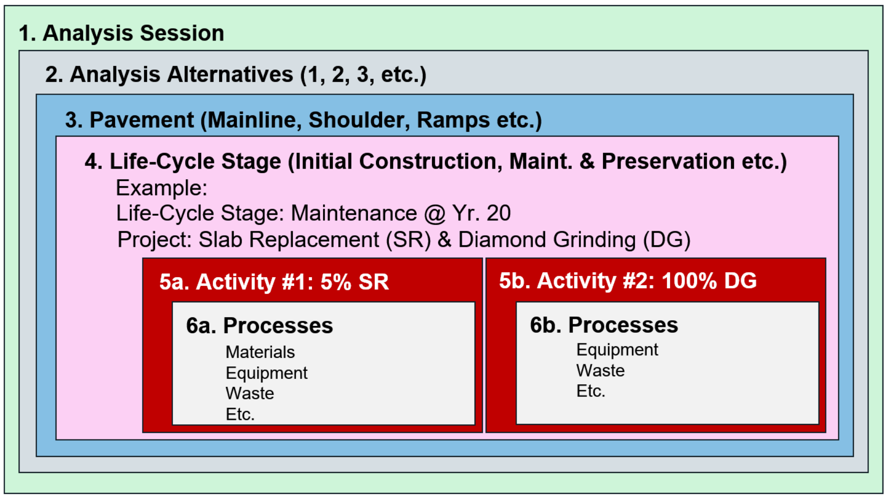

Figure 2-3. Tool structure.

2.7 AGENCY CUSTOMIZATION

Agencies can add, edit, store, and retrieve agency-specific:

- Activities.
- Mix designs.
- Regional EPDs for materials, composite materials and elements.

The tool does not include a default library of reference projects; however, an agency could create its own default library to help illustrate the types of information used to conduct an analysis.

CHAPTER 3. TOOL DATA

This chapter describes the data sources that are used in the tool and presents the results of the data quality assessment. Also discussed is the potential use of EPDs as a secondary data source. The tool has been populated with available national average or closest equivalent publicly available data. Appendix B provides additional details on the specific data and data sources.

3.0 DATA FLOWS

Each unit process is modeled using the following flows:

- Inputs (used in the process).
  - Materials.
  - Energy (heat, fuel, etc., and derived from user inputs of utilization [hours of operation, miles traveled, etc.]).
- Outputs (produced from the process).
  - Products.
  - Emissions to air, water, and land.
  - Waste for treatment.

3.1 UNIT PROCESSES INCLUDED IN THE TOOL

The basic approach for the database is to model unit processes, which have as inputs material resources and energy and have as outputs the product, waste, and emissions, as shown in figure 3-1.

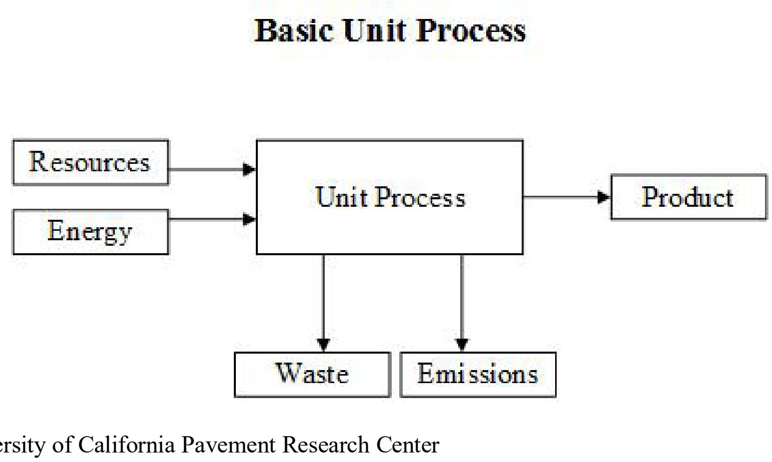

Figure 3-1. Basic unit process set up for all material, construction and transportation processes in an activity.

The models of the unit processes are as complete as possible and generally fall within the cut-off criteria[8] shown in table 3-1.

[8] Documentation of study exclusions such as the amount of material or energy flow or the level of environmental significance associated with unit processes.

Table 3-1. Cut-off criteria for tool data.

Item	Cut-Off Criteria (all criteria to be met to be excluded)
Mass	If a flow is less than 1% of the cumulative mass of the model, it may be excluded.
Energy	If a flow is less than 1% of the cumulative energy of the model, it may be excluded.
Environmental relevance	If a flow meets the above criteria for exclusion yet is thought to potentially have a relevant environmental contribution to any of the impact indicators that are analyzed with the tool, it may still be included. This judgment is based on the experience of the analyst but also relies on the literature data used in the tool. An example would be a lightweight material but with a relatively large environmental impact as compared to other materials considered. The analyst typically documents the reasons for including any data that otherwise may qualify for exclusion.
Total of Mass, Energy, and Environmental Relevance	The sum of the neglected material or energy flows does not exceed 5% of mass, energy or environmental relevance for flows indirectly related to the process (e.g. operating materials).

3.2 DATA QUALITY

3.2.1 Assessment

All data are evaluated using a data quality assessment that is based on the U.S. EPA's pedigree matrix (Edelen and Ingwersen 2016). The U.S. EPA's pedigree matrix has been enhanced for improved specificity for Pavement LCA applications aiming to standardize the practice of data quality assessment for the pavement LCA domain. The applied criteria presented in table 3-2. The scoring categories used for each criterion are presented in Appendix B. Reporting and interpretation of the obtained data quality are important to ensure that data used to determine flows, calculate impacts, and perform sensitivity analysis for the interpretation of the results are sufficient to meet the goals of the study.

3.2.2 User Input

Tool users are encouraged to establish the typical data for common inputs using the suggestions shown in table 3-3.

3.3 INCLUSION OF EPD DATA

Users can add items to the database using cradle-to-gate data available from EPDs. This includes, but is not limited to, EPD data for individual materials or mix designs. Figure 3-2 shows the case of the tool calculating impacts for a composite material from its internal data and figure 3-3 shows substitution of internal data with EPD impacts for some of the materials in the composite material.

Table 3-2. Data quality criteria and scoring.

Data Quality Category	Criteria
Reliability	Are the inventory data checked for mass/ energy balance, recalculation etc.?
Reliability	What is the status quo for the ownership and continuous support of data?
Reliability	Are the data regularly updated? Are the data of deterministic nature or are there statistically established confidence intervals stated for the data?
Data Collection Methods	How representative are the data of the market?
Data Collection Methods	How compatible is the life-cycle inventory data with TRACI 2.1 impact assessment method from LCA Commons?
Time period	How old are the data?
Time period	Do the data capture seasonal variations?
Geography	How well is the geography of the data correlated with the data quality objective?
Technology	How well is the material covered in the data correlated with the data quality objective?
Technology	How well is the technology of the data correlated with the data quality objective?
Process Review	How well is the process reviewed?
Process Completeness	How complete is the process?

Table 3-3. Data input suggestions.

Inputs	Suggestions
Project design	Follow actual design dimensions and record the life cycle stage of the design process the data are taken from.
Hauling distances	Establish agency defaults or use project-specific information based on supplier, contractor, and project locations. Evaluate these defaults periodically.
Mix design	Use approved mix designs following the appropriate agency standards.
Sequencing schedules	Establish agency defaults based on pavement types following a similar process as used for LCCA when available. Evaluate these defaults periodically.
Waste treatments	Establish agency defaults for waste treatment based on state regulation, project and waste treatment locations. Evaluate these defaults periodically.

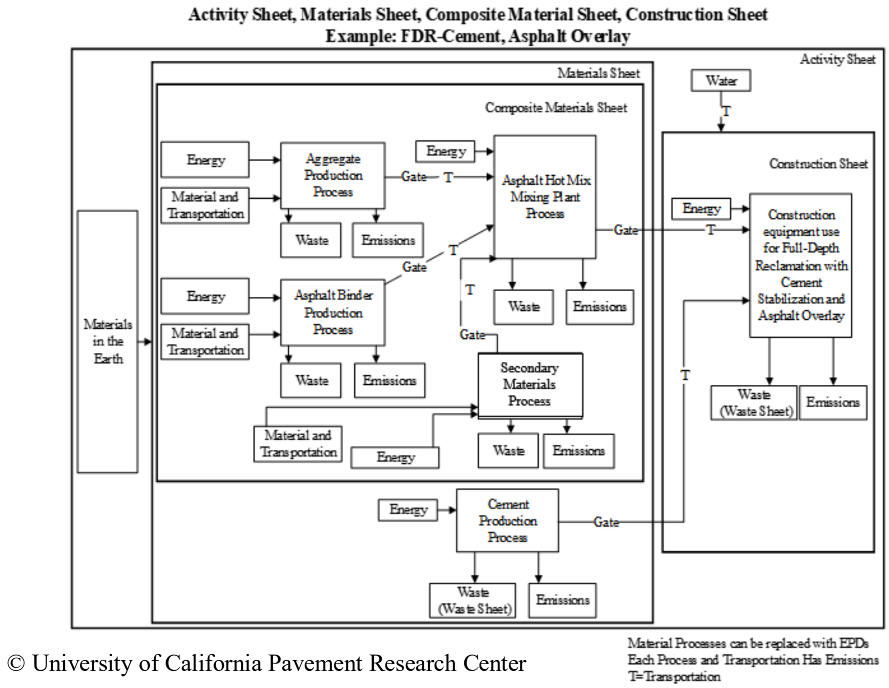

Figure 3-2. Activity sheet where users identifies a composite material using a mix design and the tool uses inventory data to calculate impacts.

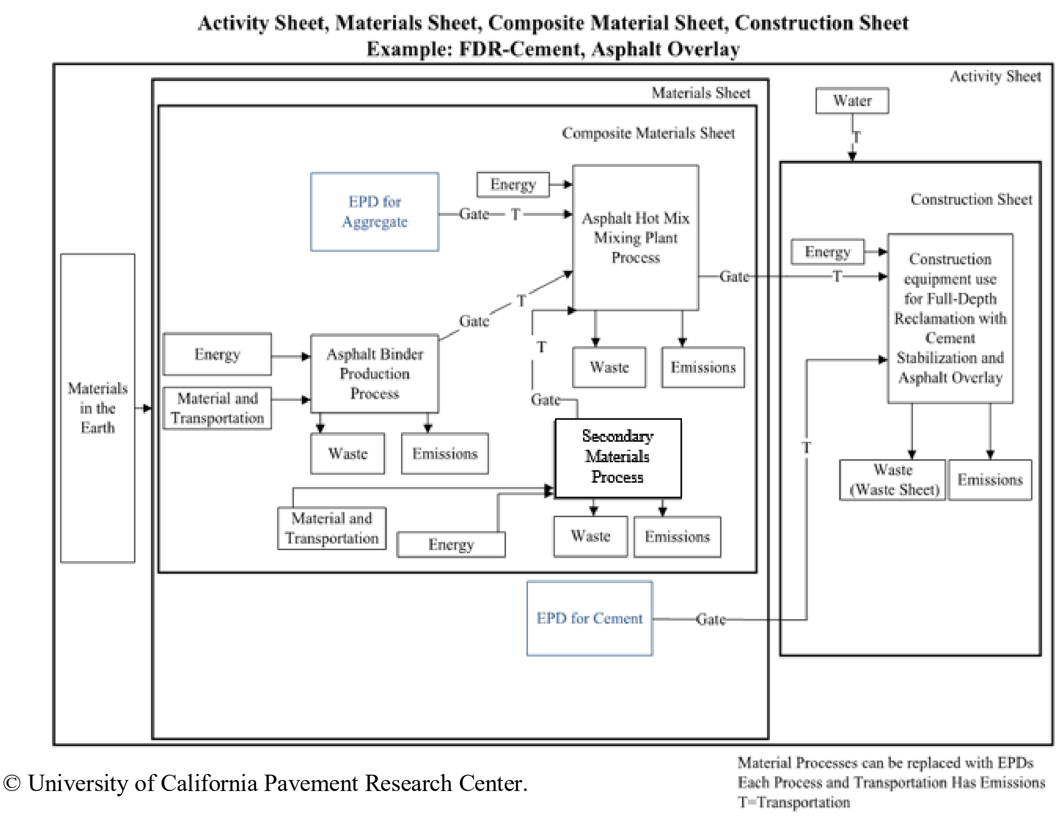

Figure 3-3. Activity sheet where the user selects a composite material using a mix design and has EPD data for some materials to replace inventory data in the tool to calculate impacts and EPD.

Table 3-4 shows several questions to consider when using EPD data in the tool. Users should be aware that discrepancies in the way that EPDs are developed may lead to results that are not indicative of actual differences in the products; furthermore, EPDs do not always contain the same impact categories and typically use a more limited set of impact indicators than what is included in the tool. This may limit the use of EPDs if the reported impact categories are different from the impact categories of interest to the agency. FHWA notes that the selection of data sources for upstream data within each EPD is often not specified in the underlying PCR document and is also not harmonized between different PCRs (Harvey et al. 2020). Mukherjee, Bhat, and Harvey (2020) provide suggestions for development of PCRs to facilitate harmonization.

Table 3-4. Considerations for including EPD data in the tool.

Questions to Consider	***….To Answer***
• Who is the developer the EPD?	*How relevant is the industry or manufacturer to the industry or manufacturers of the material to be used in the pavement in the study? Is industry-average data sufficient for the goal of the study or is manufacturer-specific data relevant?*
• What material(s) does the EPD cover?	*Is the material, its specification, and manufacturing technology fit for the purpose intended in the study?*
• What PCR was used to develop the EPD?	*Is the PCR within its validity period or is it expired (out of date), and does it follow best practices for harmonization?*
• What is the functional or declared unit?	*What is the unit / amount of product that is used to present all the result of the EPD ("this amount or environmental result per this amount of product") and how does that translate to the use in the project being studied?*
• What are the system boundaries?	*What is included in the results and what is not? Are the life cycle stages, full set of materials, manufacturing processes, etc. consistent with the intended material to be used by the agency or in the pavement being studied?*
• What year(s) are the data from?	*Looking at the data used to produce the EPD, are they consistent with the processes and materials used for the agency or project being studied.*
• What are some key assumptions stated?	*Look for key assumptions to see if the EPD is a good fit for the project or agency*
• What is the environmental impact assessment methodology used and what impact indicators are reported?	*Does the EPD show TRACI 2.0 impact categories (discussed in Chapter 5)? Does it include a full list when looking at the FHWA LCA Framework or not, if not, is that still appropriate, or, does it cover the impact categories that the agency is interested in? Note that there are different calculation methods for the same impact category between different impact category systems, such as between TRACI 2.0 and CML.*

CHAPTER 4. IMPACT ASSESSMENT METHODOLOGY

This chapter presents the impact categories that are included in the tool, and the way that they are considered in the analyses.

4.0 IMPACT INDICATORS

The tool offers a range of impact indicators that consist of a selection of Life-Cycle Inventory flows (LCI) and Life-Cycle Impact Assessment indicators (LCIA) (see tables 4-1 and 4-2).

Table 4-1. List of LCI flows.

Impact Indicator	Name in Tool	Unit	Methodology
Use of renewable primary energy, excluding renewable primary resources used as raw materials	Renew. Energy (Non Raw Matl)	MJ, net calorific value	Total of used energy resource
Use of renewable primary energy resources used as raw materials	Renew. Energy (Raw Matl)	MJ, net calorific value	Total of used energy resource
Total use of renewable primary energy resources	Total Renew. Energy Use	MJ, net calorific value	Total of used energy resource
Use of nonrenewable primary energy, excluding nonrenewable primary energy resources used as materials	Nonrenew. Energy (Non Raw Matl)	MJ, net calorific value	Total of used energy resource
Use of nonrenewable primary energy used as raw materials	Nonrenew. Energy (Raw Matl)	MJ, net calorific value	Total of used energy resource, including feedstock energy
Total use of nonrenewable primary energy resources	Total Nonrenew. Energy	MJ, net calorific value	Total of used energy resource
Recycled material usage	Recycled Matl. Use	Short-tons	Total of used recycled material by type
Recycled material usage	Recycled Matl. Use	Percentage	Percentage of total of used recycled material by type as part of the total of used recycled and not-recycled material
Disposed non-hazardous waste	Disposed non-hazardous waste	Short-tons	Total of non-hazardous waste material by type that goes to landfill
Disposed hazardous waste	Disposed hazardous waste	Short-tons	Total of hazardous waste material by type that goes to a sanitary landfill
Disposed radio-active waste	Disposed radio-active waste	Short-tons	Total of radioactive waste material by type that goes to a radioactive waste site
Net use of fresh water	Net use of fresh water	Cubic meter	Total net use of fresh water
Supplementary Cementitious material (SCM) usage	SCM Usage	Short-tons	Total of used SCM by type
Supplementary Cementitious material (SCM) usage	SCM Usage	Percentage	Percentage of total of used SCM by type as part of the total of used binder content in cement concrete

Table 4-2. List of LCIA indicators (based on TRACI, Bare 2012; Bare et al. 2012).

Impact Indicator	Name in Tool	Unit	Methodology
Acidification	Acidification	kg SO_2 eq	TRACI 2.0
Ecotoxicity	Ecotoxicity	CTU_{eco}/kg	TRACI 2.0
Eutrophication	Eutrophication	kg N eq	TRACI 2.0
Fossil Fuel Depletion	Fossil Fuel Depletion	MJ surplus	TRACI 2.0
Global Warming	Global Warming	kg CO_2 eq	TRACI 2.0, 100-year
Human Health – Cancer	Human Health – Cancer	CTU_{cancer}/kg	TRACI 2.0
Human Health – Noncancer	Human Health – Noncancer	$CTU_{noncancer}$/kg	TRACI 2.0
Human Health Effects – Particulates	Human Health Effects – Particulates	kg $PM_{2.5}$ eq	TRACI 2.0
Ozone Depletion	Ozone Depletion	kg CFC-11 eq	TRACI 2.0
Smog formation	Smog formation	kg O_3 eq	TRACI 2.0

Where flows show a certain volume, LCIA results aim to better understand their environmental significance. The list of impact indicators shown in tables 4-1 and 4-2 is based on FHWA's framework document (Harvey et al. 2016). This list is the default for showing results in the tool, but it can be tailored by the user.

The tool does not always include all impact indicator results for all library items. The tool provides insight to the user about the completeness when selected an item from the database and when the result outputs are displayed.

Normalization, grouping, or weighting are not part of the impact assessment in the tool. Additionally, the tool does not evaluate the social or economic aspects of the sustainability "triple-bottom line," and hence it does not include impact indicators such as noise, safety, jobs, cost, etc. Other tools are available from the FHWA (e.g., RealCost, INVEST) for evaluating those factors. Tool users can consider these and other factors of interest as part of the decision-making process.

It is important to point out that feedstock energy of material resources is reported under the appropriate "primary energy used as materials" category and is thus included in the "total energy" category.

4.1 IMPACT ASSESSMENT METHODOLOGY USED IN THE TOOL

The impact indicators that are based on flows provide a summation of the flows throughout the model. The energy impact indicators are based on average national energy content and types. All other impact indicators are based on the U.S. EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) impact assessment method (Bare 2012; Bare et al. 2012).

CHAPTER 5. INTERPRETATION AND REPORTING

This chapter describes the reporting of results and the suggested methodology for interpreting the findings and results. The tool itself does not interpret the results.

5.0 RESULTS PRESENTATION

Results are presented in a variety of ways starting with the total impacts and followed by several *contribution analyses* in which the contributions of life-cycle stages or groups of activities to the total result are shown. The contributions are presented in both graphs and tables with totals or expressed as percentages of the total with the options shown in table 5-1.

Table 5-1. Options for presenting results.

Item	Options
Alternative Definition	• All user selected and modeled items as part of the tree for the alternative, including volumes and notes
Comparisons	• Comparison between two alternatives on totals, absolute and relative, for all impact indicators, to be used when same analysis periods and functional units are compared. (Note that if alternative functional units are being compared, it is the responsibility of the user to correctly identify the different functional units in the reporting because the tool does not have this capability). • Comparison between annualized totals, absolute and relative for all impact indicators when unequal analysis periods are compared.
Alternative	• Results for each alternative showing all user selected items in the alternative tree, absolute and relative, for all impact indicators, including an indication of completeness of aggregated results per indicator • Result, absolute and relative, broken down by − pavement facility (mainline, shoulder etc.) − life-cycle stage (initial construction, rehabilitation etc.) − activity type (layers, surface treatments etc.) − process type (material, equipment etc.) − application age (treatment sequences over time) • Relative results are shown in tables and graphs

5.1 INTERPRETING LCA RESULTS

The interpretation of the LCA results should focus on answering the goals of the study. If the study is only for reporting, then data quality—in particular, completeness and geographic and temporal applicability—should be provided with the results.

When answering an LCA goal other than just reporting, interpretation of the LCA results commonly consists of the following:

1. **Identification of significant issues (major contributions, or gravity analysis)**. The results presentation allows for a *contribution analysis* in which the contributions of life-cycle stages or groups of processes to the total result are examined (often done by expressing the contributions as percentages of the total). The tool provides data completeness reports that support this type of interpretation.

An *anomaly assessment* may also be performed in which the results are scanned for any unusual values or significant deviations. The identification of anomalies is often based on the experience of the user and may lead to changes in the user input data and a rerun of the interpretation.

2. **Evaluation of results for completeness, sensitivity, and consistency**. Uncertainty and sensitivity are important topics to include in the interpretation and its communication to the study's audience. Uncertainty can be found in the underlying data (as addressed in the section on LCA methodology in this document) and also in the uncertainty of selection, choices, and assumptions made by the user. Particular attention should be paid to the major contributors to the impacts of interest and their potential uncertainty, which can be evaluated through a sensitivity analysis to assess the validity of the results. The findings of the sensitivity analysis are typically included in the overall analysis results. Sensitivity analyses can consider the following topics, although the list is not comprehensive:

   - The uncertainty of timing of treatments in the life cycle because of variability of service life for materials and treatments. This is especially important when comparing alternatives. The tool has the ability to include a sensitivity analysis for performance of activities in terms of the year in which the succeeding activity occurs.
   - The estimate for material types and quantities for treatments with potentially varying degrees of uncertainty about quantities for different alternatives.
   - The influence of the choice of the analysis period.
   - The use of data with different regional representativeness for materials suppliers within the same analysis.
   - The selection of impact categories for reporting.

   Because the tool does not have the capability to do probabilistic modeling of input variables, repeated sensitivity analyses may be performed to assess the influence of variable variance, as described below:

   - For the most important variables contributing to impacts of interest, conduct the analysis in the tool using the most likely (median), the minimum, and the maximum expected values for the variables. Where more information is available regarding the probability distributions of variables and if they are normally distributed, an alternative approach is to conduct the analysis for the mean and plus/minus one or two standard deviations of the mean, and incorporate the statistical meaning of those ranges into the interpretation. This can be done by varying each variable while holding other important variables at their best estimate value, or to get a more complete idea of the robustness of the comparison as a full factorial for all permutations of all important variables.
   - When there is likely to be a very wide distribution of the values of an important variable, and the maximum and minimum values have very small likelihoods of occurring, an alternative is to conduct the analysis for the expected most likely value and the expected most likely value plus/minus one standard deviation. The two options given above can be performed with these three values. The range of values

for variables in this case covers approximately 85 percent of the range of the variables as opposed to 100 percent of the range for the approach given above.

To assess the sensitivity of the results to system boundaries, analysis periods, and user assumptions not associated with uncertainty, the LCA should be conducted with the alternative assumptions to determine if it changes the results enough to change the interpretation. The tool supports comparison reporting that can be used to compare results from sensitivity analysis.

When comparing alternatives and interpreting results, it is common to consider alternatives with differences of 10 to 20 percent (or less) as not different enough to conclude one is better than the other. This percentage range is arbitrary and should be applied on a case-by-case basis.

The user is encouraged to review the completeness and consistency of the information for each alternative listed in the tool's Alternative Definition worksheet.

3. **Drawing conclusions and checking consistency with the goal and scope**. Conclusions can include lessons learned from the previous two steps. This section should include conclusions, a discussion of limitations and recommendations, discussion of the confidence about assumptions made in the LCA (particularly if complete life cycle stages are not compared, for example the use stage). The results of contribution analyses and sensitivity analyses should be included in the reporting of the LCA study.

It is suggested to use the full list of energy flows and TRACI impact indicators of interest and to not use weighting or aggregation of indicators in interpretation.

5.2 REPORTING

5.2.1 Internal Reporting

Agencies can establish an internal review and/or authorization process for signing off on the project analysis and for describing how results are reported, presented, and archived. The tool features a template project report and extensive results views available as an export. The analysis report should include the following sections:

- Analysis description (can be documented input in tool interface).
  - Introduction to the pavement project itself.
  - Type of LCA and critical assumptions, including confidence in critical assumptions.
  - Life-cycle phases included, with documentation of assumptions made if less than full life-cycles were considered.
- Agency goal for the analysis (can be input in tool interface).
  - Reason for carrying out the analysis.
  - Target audience.
  - Type of critical review.
- Summary of treatment life cycles and materials quantities used (available in tool outputs).
- Results (available in tool outputs).

  - User selection of tables and plots from tool options [see tool user manual (Ram et al. 2021)].
  - Results of sensitivity analyses (conducted separately by the user).
- Interpretation (to be performed by user outside of tool).
  - Summary of completeness assessment and sensitivity analyses.
  - Conclusions and lessons learned.
  - Limitations recognized by the user.
  - Recommendations.
  - Robustness of conclusions and recommendations.
- Indication of the use of (all) defaults or (some or only) user input (available in tool outputs).
- Warnings/limitations: analysis type indicating whether it was a full life-cycle or a comparative analysis, impact indicators that are not considered, or incomplete set of impact indicators. The user is encouraged to note other limitations and assumptions within the tool interface.
- Date, version, agency, and user.

Users can report the energy flows and TRACI impact indicators of interest and can elect to not use or show weighting or aggregation of indicators in the interpretation. It is suggested that an LCA expert not involved in the LCA study be engaged for a critical review when the user is planning to make agency recommendations related to pavement design, construction, sequencing of treatments, end-of-life decisions, or other policy changes. A critical review may not be needed for other use-cases but may still be used by an agency to increase the quality, transparency, and buy-in of the results.

5.2.2 External Reporting

Agencies can use the tool for internal purposes to gain familiarity, establish good practices, and obtain meaningful and consistent results. Any external use of the outputs of the tool should go through a dedicated agency process. Agencies can establish an authorization process for signing off on the project analysis and for describing how results are reported, presented, and archived internally. A third-party review for comparative analysis is suggested for external communication, consisting of at least three experts possessing a mix of LCA and domain knowledge on the committee (ISO 2006a).

CHAPTER 6. SUMMARY

This chapter provides an overall summary of the background work for the tool development efforts including assumptions, limitations, and data gaps.

6.0 TOOL SUMMARY

A first version spreadsheet tool has been developed for conducting LCA of pavement systems. The tool has been populated with national averages or closest equivalent of publicly available data. The tool is fully functional for the materials production, construction, and end-of-life stages, including transportation of materials. It does not, however, currently support inclusion of any use stage processes. The initial database included in the tool has undergone a data quality assessment following a data quality matrix adapted from other Federal agency efforts.

6.1 ASSUMPTIONS

The tool is intended for use as a training and informational product only and for use by agencies and individuals knowledgeable of LCA principles. The LCA data for the library items follows an allocation approach that is most closely related to general practices in EPDs for recycled content and for material that is to be recycled. The impact assessment methodologies and data availability and quality may change with time. The methodology follows an attributional approach and specifically does not follow a consequential approach.

6.2 LIMITATIONS

The tool uses publicly available data for transparency, which creates some gaps in the background data. Where possible, these gaps have been filled with other available data, which may affect some of the results as the substitute data may be dated or may not completely reflect practices in the U.S. Users should be aware of these data limitations when performing these analyses.

The tool allows for the use of EPD data. This should be done with caution as there is a need for further harmonization between different EPD programs.

The tool does not consider any use stage processes, which leaves out the effects of work zones (e.g., work zone speed changes, travel delay and diversions), pavement-vehicle interaction and related fuel use and emissions, ice and snow management, storm water runoff, heat island effects, and carbonation.

6.3 DATA GAPS

The tool's database sought to use publicly available data reflective of U.S. practices and to include a complete set of impact categories. Current limitations in data quality and data availability prevented that, resulting in some gaps in the database. Where possible, these gaps were filled with other available data to allow for a fully functional tool, but these workarounds may affect some of the results as the substitute data may be dated or may not completely reflect U.S. practices.

An additional source of information for mix design components comes from several EPDs. Where EPDs were not available, other sources of information were used, including U.S. based industry or contactor data and data from the available literature (some of which comes from Europe).

Similarly, where gaps in the provided impact categories were present, these were filled with data from other sources. Because some EPDs did not include TRACI impact categories units but instead relied on CML impact assessment for some of the impact categories, these were converted to the appropriate units for use in the tool.

Data used in the equipment library comes from the U.S. EPA MOVES tool (EPA 2014) and was supplemented with fuel consumption ratings data. Data gaps in the equipment library were not addressed.

The end-of-life processing data set is one area that needs improvement. Data from a U.S. EPA project (Niblick et al. 2020) has produced several waste treatment processes, but the scope is limited where it relates to specific pavement materials for landfill. It is making inroads into defining processes for handling and processing for reuse and recycling, but the scope is currently limited.

Transportation data are based on two main data sources: USLCI data from the U.S. NREL for transportation in general and U.S. EPA emission data for more pavement-specific transportation where estimates of fuel consumption have been be applied. The energy impact categories were missing from the USLCI data as published in OpenLCA, some of which have been added using USLCI data as published in other sources.

6.4 IMPLEMENTATION

It is suggested that agencies pilot the use of the tool and explore how the results can be interpreted, applying their own practices and knowledge of pavement engineering and LCA principles. Agencies can also start to request EPDs from industry to populate the tool library. The use of EPDs is not required by Federal regulation or statute.

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APPENDIX A. GLOSSARY

A list of terms used in this report is provided in table A-1.

Table A-1. Glossary.

Term	Description	Source
Activity	A discrete event that changes a segment/section/area of pavement that involves one or more flows and/or processes. Includes all materials, composite materials, elements, equipment, hauling, construction processes and waste treatments associated with that change.	NA
Alternative	A user-identified version of the model of the project making use of the line item database to create a sequence of activities for a specific period of time (the analysis period). Different alternatives can be modeled and compared.	NA
Analysis period	The time period in years for which an alternative is modelled.	NA
Background data	Data that is not owned or controlled by transportation agencies or contractors.	NA
Composite Material	A material that has a mix design for proportioning two or more ingredients. Includes identification of ingredient materials in database. Examples are asphalt concrete, hydraulic cement concrete, stabilized aggregate materials, aggregate materials that have two sources (such as coarse and fine, or recycled material and virgin material)	NA
Element	Something used in the pavement structure that has a pre-formed shape prior to arriving at the construction site. Examples include dowels, tire bars, fabric interlayers, pipes.	NA
End-of-waste state	A material has reached the end-of-waste state when it complies with all the following criteria: - the recovered material, product or construction element is commonly used for specific purposes. - a market or demand, identified e.g. by a positive economic value, exists for such a recovered material, product or construction element. - the recovered material, product or construction element fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products. - the use of the recovered material, product or construction element does not lead to overall adverse environmental or human health impacts.	EN15804
Equipment	A piece of equipment that is used for activities or pay items.	NA
Feedstock Energy	Nonfuel energy use: the energy used as a raw material for purposes other than for heat, power, and electricity generation	US Energy Information Administration
Foreground data	Data owned or controlled by transportation agencies or contractors.	NA
Hauling	A means of transportation that is used for bringing materials to a processing plant or bringing and hauling materials and equipment to and from the job-site.	NA
Item	A line item in the database that consists of activities, composite materials, elements, equipment, hauling, materials, pay items and waste treatments needed to model any alternative.	NA
Material	Something used in the pavement structure that does not have a pre-formed shape prior to arriving at the construction site	NA

Term	Description	Source
Mix design	Material that is formed by combining two or more materials of a single type from different processes, with the mixing being another process, created following a mix design that relates the relative proportions of the component materials in the mixing process.	NA
Pavement	An object with varying numbers of hard surfaced lanes, which may include an inner and outer shoulder, that can all have several layers including a base and subgrade.	NA
Pavement life cycle	A series of discrete projects in time within an identified performance (and hence analysis) period. The Pavement Life Cycle considered in the scope of this study can include, all or only some of these stages, and is assigned by the user within an alternative: - Initial construction - Preservation - Maintenance - Rehabilitation - Removal - Reconstruction	NA
Pay item	An activity that is assigned a monetary value as part of the contracting process by an agency	NA
Product system	A set of connected unit processes that create a product.	NA
Project	A pavement project that the user wants to model, or, a user-defined set of activities that are completed over a discrete period of time that are organized together in a coordinated manner to transform a segment/section or area of pavement, often within a single contract.	NA
Unit Process	Smallest element considered in the life-cycle inventory analysis for which input, and output data are quantified. In other words, a collection of input flows that is converted into a set of output flows including output product(s). This includes relevant energy and raw materials inputs that are converted into outputs of products, co-products, by-products, waste and emissions.	ISO 14044
Upstream data	Data that comes before a unit process owned or controlled by transportation agencies or contractors.	NA
Waste treatment	A process that handles a material waste flow.	NA

APPENDIX B. TOOL DATABASE

This appendix describes the approach and selected data sources to the various data libraries in the tool. The tool includes data for users to build their analysis that all follow a similar data format which is discussed below. This appendix then provides an overview for the data libraries for materials, equipment, waste, transportation, fuels and electricity. The work described in this appendix is the result of a collaboration of the tool project team and the work done by MTU and TRE under the parallel FHWA study. More specific details, the actual data and sources are available upon request through FHWA.

TOOL DATABASE FORMAT

The tool has several data libraries that all follow the same structure. Descriptions of meta data and data quality are available in Chapter 3. Table B-1 summarizes the general library item characteristics included in the tool and table B-2 provides the data quality assessment ratings. Metadata and data quality information are reported in the tool.

Table B-1. General item characteristics.

Unique ID	ID for tool use
Material Type	To cluster materials into categories for easier look up by the user
Material Name	Name of the material
Measure Type (Length, Area, Volume, etc.)	How the amount is measured
Quantity	How much of it is represented by the data
Units	How the amount is measured
Mass Conversion Factor (Lb Per Unit)	Conversion to allow for mass-based calculations in the tool
Agency ID	Free field for Agencies to allow to identification, like a state approved mix design code
Description	General information on what is represented by the data
Editable? (Default or User-Identified)	Categorization to make sure default data that comes with the tool libraries are not changed and to make sure user edits are transparent
From EPD?	Identification of whether the data source is an EPD

LCI Flows included for the tool's library items are listed below:

- Use of renewable energy primary energy, excluding renewable primary resources used as raw materials (MJ).
- Use of renewable primary energy resources used as raw materials (MJ).
- Total use of renewable primary resources (MJ).
- Use of nonrenewable primary energy, excluding nonrenewable primary energy resources used as materials (MJ).
- Use of nonrenewable primary energy used as raw materials (MJ).
- Total use of nonrenewable primary energy resources (MJ).
- Recycled material usage (shortTon).

- Recycled material usage (%).
- Disposed non-hazardous waste (shortTon).
- Disposed hazardous waste (shortTon).
- Disposed radio-active waste (Short-tons).
- Net use of fresh water (Cubic meter).
- Supplementary Cementitious material (SCM) usage (shortTon).
- Supplementary Cementitious material (SCM) usage (%).

LCIA results included for the tool's library items are listed below:

- Acidification (kg SO_2 eq).
- Ecotoxicity (CTUeco/kg).
- Eutrophication (kg N eq).
- Fossil Fuel Depletion (MJ surplus).
- Global Warming (kg CO2 eq) (100-year time frame)
- Human Health – Cancer (CTUcancer/kg).
- Human Health – Noncancer (CTUnoncancer/kg).
- Human Health Effects – Particulates (kg PM2.5 eq).
- Ozone Depletion (kg CFC-11 eq).
- Smog Formation (kg O_3 eq).

Administrative metadata fields included in the tool's library are listed below:

- Name/initials of person recording the data.
- Source of data/model calculations.
- Data produced/published (Year).
- Data accessed/recorded (DDMMYY).

Descriptive metadata fields included in the tool's library are listed below:
.

- Flow type/describe/name (ex-PG64-15)
- Location where data is produced.
- Other properties.

Table B-2. Data quality assessment rating scale.

Criterion	Details	Data Quality Score 1	Data Quality Score 2	Data Quality Score 3	Data Quality Score 4	Data Quality Score 5
Reliability	Are the inventory data checked for mass/ energy balance, recalculation etc.?	Verified data based on measurements	Verified data based on a calculation or non-verified data based on measurements	Non-verified data based on a calculation	Documented estimate	Undocumented estimate
Reliability	What is the status quo for the ownership and continuous support of data?	Hosts and Owns	Owns but does not host	Hosts but does not owns	Hosts and owns partially	Does not host or own
Reliability	Are the data regularly updated? Are the data of deterministic nature or are there statistically established confidence intervals stated for the data?	Regular updates Confidence Intervals developed considering parameter, scenario and model uncertainty based on directly measured or calculated data	Less frequent updates Confidence Intervals developed considering either of parameter, scenario and model uncertainty based on assumed probability distribution	No updates Deterministic value provided	N/A	N/A
Data Collection Methods	How representative are the data of the market?	Representative data from >80% of the relevant market, over an adequate period	Representative data from 60-79% of the relevant market, over an adequate period OR representative data from >80% of the relevant market, over a shorter period	Representative data from 40-59% of the relevant market, over an adequate period OR representative data from 60-79% of the relevant market, over a shorter period	Representative data from <40% of the relevant market, over an adequate period OR representative data from 40-59% of the relevant market, over a shorter period	Unknown OR data from a small number of sites and from shorter periods
Data Collection Methods	How compatible is the life-cycle inventory data with TRACI 2.1 impact assessment method from LCA Commons?	Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method	Life-cycle inventory data is enough to calculate only 6 out of 9 mid-point indicators as per TRACI 2.1 impact assessment method	Life-cycle inventory data is enough to calculate only 3 out of 9 mid-point indicators as per TRACI 2.1 impact assessment method	Life-cycle inventory data is not compatible with TRACI 2.1 impact assessment method from LCA Commons	N/A

Table B-2. Data quality assessment rating scale (continued).

Criterion	Details	Data Quality Score 1	Data Quality Score 2	Data Quality Score 3	Data Quality Score 4	Data Quality Score 5
Time period	Do the data capture seasonal variations?	All three (fall, spring and summer) seasons are covered	Only two out of three seasons are covered	Only one season is covered	Not Specified	N/A
Time period	How well is the time period the data correlated with the data quality objective?	Less than 3 years of difference	Less than 6 years of difference	Less than 10 years of difference	Less than 15 years of difference	Age of data unknown or more than 15 years
Geography	How well is the geography of the data correlated with the data quality objective?	Data from same resolution AND same area of study	Within one level of resolution AND a related area of study	Within two levels of resolution AND a related area of study	Outside of two levels of resolution BUT a related area of study	From a different or unknown area of study
Technology	How well is the technology of the data correlated with the data quality objective?	All technology categories are equivalent	Three of the technology categories are equivalent	Two of the technology categories are equivalent	One of the technology categories are equivalent	None of the technology categories are equivalent
Technology	How well is the material covered in the data correlated with the data quality objective?	Specific material from specific regional supplier	Specific material from (group of) supplier(s) of relevant geography	Specific materials, but from different geography	Similar material, from relevant geography	Different material
Process Review	How well is the process reviewed?	The process has documented reviews by a minimum of two types of third-party reviewers	The process has documented reviews by a minimum of two types of reviewers, with one being a third party	The process has documented review by a third-party reviewer	The process has documented review by an internal reviewer	The process has no documented review
Process Complete-ness	How complete is the process?	>80% of determined flows within the process have been evaluated and given a value	60-79% of determined flows within the process have been evaluated and given a value	40-59% of determined flows within the process have been evaluated and given a value	<40% of determined flows within the process have been evaluated and given a value	Process completeness not scored

MATERIALS

A list of the most commonly used road construction materials was developed and the background, upstream and foreground data fields for the list of materials identified. UCPRC and theRightenvironment worked jointly on the foreground data which includes material mixes, material production LCIs and LCIAs, etc. The data, mainly LCIs (energy and material flows) and LCIAs (TRACI/CML mid-point indicators), for the materials was collected from several sources. The goal of the team was to collect the best publicly available data that could be considered as adequate and sufficient for the pavement LCA users such as the agencies.

The approach to collect the materials data is chronologically presented below:

1. Search for publicly available material EPDs in the USA.
   a. product plant specific EPD preferred.
   b. industry-average EPD.
   c. approach/contact industry for EPDs and/or clarifications for any incomplete data, if required.
2. LCA of materials found in the literature for USA.
   a. a complete material LCA available in the literature (reports, journals, conference papers).
   b. an incomplete material LCA available in the literature.
3. Assume and perform calculations if required so the data fulfils the USA geographic and environmental conditions.
4. Search for publicly available material EPDs published elsewhere other than USA.
5. Search for material LCAs performed in other parts of the world excluding USA.

The list of materials is divided into two major categories: unit process materials and mix design materials. Unit process materials are the materials that can be combined/mixed to form secondary materials whereas mix design materials (the secondary materials) are developed using the unit process materials.

The list of materials further classified by material type:

- admixture/additive.
- aggregate.
- asphalt binder.
- cementitious.
- element.
- other.
- recycled waste materials (RCWM).
- steel.

EPDs have been used for the following materials:

- Accelerating Admixture (Hardening)
- Accelerating Admixture (Set)
- Air Entrainer
- Curing Compound
- Other Chemical Admixtures for Concrete
- Plasticizer

- Retarding Admixture
- Water Proofing Agent
- Base and Subbase Material
- Granite (for chip seal application)
- Concrete Sand
- Crushed Stone (Coarse Aggregate for Concrete)
- Crushed Stone, granite (Coarse Aggregate for Asphalt)
- Crushed Stone, granite (Coarse Aggregate for Concrete)
- Fine Aggregate (for asphalt)
- Fine Aggregate (for concrete)
- Paraffin Wax
- Sealer / Rejuvenator
- Cement (Blended with SCMs)
- Cement (Precalciner method)
- Slag Cement
- Precast Concrete
- Primer White Paint
- Ground Granulated Blast Furnace Slag (GGBFS)
- Recycled Concrete Aggregate (RCA)

Other literature sources have been used for the following materials:

- Asphalt binder, 0.5% polyphosphoric acid (PPA), consumption mix, at terminal, from crude oil, 0.5% polyphosphoric acid
- Asphalt binder, 3.5% styrene-butadiene-styrene (SBS), consumption mix, at terminal, from crude oil, 3.5% styrene-butadiene-styrene
- Asphalt binder, 8% ground rubber tire (GRT), consumption mix, at terminal, from crude oil, 8% ground rubber tire
- Asphalt binder, no additives, consumption mix, at terminal, from crude oil
- Liquid Asphalt Binder, in refinery
- Liquid Asphalt Binder, with Polymer
- Fly ash
- Silica Fume
- Geotextile fabric
- Rubber
- Lime, Hydrated
- Water
- Ground Tire Rubber (GTR)
- Reclaimed Asphalt Pavement (RAP)
- Recycled Asphalt Shingles (RAS)
- Steel, Reinforcing
- Steel, Reinforcing, Epoxy-coated
- Steel, Rod, Galvanized
- Steel, Stainless
- Dowel bar, 1.5-inch diameter x 18 inches long

- Dowel bar, 1.25-inch diameter x 18 inches long
- Tie-bar, threaded

As noted earlier, fuels and electricity have also been included in the materials library in the first version of the tool. These items may feature in separate libraries in future version of the tool.

EQUIPMENT

During construction, fuel is consumed by construction equipment being used in the construction process. At national level, US Environmental Protection Agency's MOtor Vehicle Emission Simulator (MOVES) model has a capability to produce energy and emissions inventory results for different construction equipment. However, the resulting output is based on a pump-to-wheel (PTW) analysis. PTW can also be characterized as foreground data. Well-to-pump (WTP) energy and emissions inventory data can be referred to as background data and summation of PTW and WTP results in a life cycle energy and emissions analysis also called well-to-wheel (WTW) analysis.

WTW analysis has been performed for the environmental emissions and results reported using TRACI indicators (Bare et al. 2012) whereas for energy purposes, only PTW results are reported. WTP energy data has been identified as gap. It is important to note that MOVES2014a [EPA 2015a] has an incomplete version of the Non-Road category that covers equipment. The most updated version of MOVES is MOVES2014b [EPA 2015b] which incorporates significant improvements in calculating Non-Road (equipment) emissions. This appendix summarizes the process of data collection and processing it for the construction equipment programmed into the FHWA pavement LCA tool.

Non-Road database (containing equipment) in MOVES mainly covers the equipment used all over the USA (at national level). A list of construction equipment that was included in the tool was developed by mapping several possible construction activities. The equipment list was then mapped against the MOVES construction equipment [EPA 2015b]. Brake specific fuel consumption (BSFC) for all the construction equipment was then acquired for each equipment per fuel type and horsepower range by running MOVES. BSFC is the rate of fuel consumed per engine power and measured as pounds of fuel use per horsepower-hour (lb/hp-hr). The results are presented in table B-6 in this Appendix. MTU and theRightenvironment have been working with the Federal Commons to identify common background datasets for LCA applications by the Federal Government in general. This outreach has resulted in background datasets that are used for the tool. The tool is making use of the following data for fuels:

Source: United States Environmental Protection Agency (EPA 2015a):

- Operation of compressed natural gas equipment, industry average >19 kW and <56 kW.
- Operation of compressed natural gas equipment, industry average >56 kW and <560 kW.
- Operation of diesel equipment, industry average <19kW.
- Operation of diesel equipment, industry average >19 kW and <56 kW.
- Operation of diesel equipment, industry average >56 kW and <560 kW.
- Operation of diesel equipment, industry average >560 kW and <900 kW.
- Operation of diesel equipment, industry average >900 kW.

- Operation of gasoline equipment, 2-stroke, industry average <19 kW.
- Operation of gasoline equipment, 4-stroke, industry average <19 kW.
- Operation of gasoline equipment, industry average <19 kW and >56 kW.
- Operation of gasoline equipment, industry average <56 kW and >560 kW.
- Operation of liquefied petroleum gas equipment, industry average <19 kW and >56 kW.
- Operation of liquefied petroleum gas equipment, industry average <56 kW and >560 kW.

Midpoint indicators based on TRACI 2.1 impact assessment method [0] were then produced using OpenLCA [GreenDelta 2020]. Life cycle impact assessment (LCIA) results for same equipment type running on same fuel but different hp engines were also investigated and it was concluded that the LCIAs are insensitive to different hp ranges. The results are reported in table B-5 of this Appendix. The energy densities in MJ per gallon of 4 different fuel types is reported in table B-6.

How to Use and Process Data in the Tool
This section details the steps that can be taken to process the data. The user *selects* the equipment type (with a pre-established horsepower range and fuel type) the from a dropdown list in the. Based on user selection, the tool calculates the LCI and LCIA impact indicators for hours of equipment use input by the user.

Example
An example has been done below in order to demonstrate how the data is used and processed in order to achieve the LCI (energy from use of non-renewable fuel) and LCIAs (all TRACI mid-point indicators).

Step 1. User Interface

i. Crane,
ii. 300 < hp <=600,
iii. Nonroad Diesel,
iv. 100 hours.

Step 2. Tool Background Processing

i. Fuel Use = 9.339 gallon/hr
ii. Total Fuel Consumption = 9.339 x 100 = 933.9 gallons

Step 3. Determine LCI and LCIAs per Process/Activity

i. Diesel = 135.5 MJ/gallon,
ii. LCI (non-renewable fuel energy) = 933.9 x 135.5 = 126544 MJ.
iii. Unit LCIAs for the fuel type used by the equipment
iv. TRACI indicators = 933.9 gallons x each value in 3-iii above in order to get results calculated by the tool.

WASTE

A consistent, but not regionalized approach using waste data from an EPA project (Niblick et al. 2020) has been used in the tool. It includes landfill data and dust emissions from stockpiles. The use of equipment for the handling of materials as part of reuse and recycling has been modeled using estimates from the Illinois Tollway for the pay-item based review of the most recent I-90 project corridor improvements. The emissions from the use of equipment are based on the same materials elsewhere in the tool. The tool includes datasets for landfill, reuse, and both on-site and off-site recycling for the following material categories:

- Aggregate
- Asphalt
- Composite
- Concrete
- Galvanized Steel
- Metal
- Plastic
- Soil
- Stainless Steel
- Steel

TRANSPORT

Outreach for transport data has identified the following life cycle inventory included in the tool, representing transport as made available by NREL:

Source: National Renewable Energy Laboratory

- Barge, Average Fuel Mix
- Barge, Diesel
- Barge, Residual Fuel Oil
- Combination Truck, Average Fuel Mix
- Combination Truck, Diesel
- Combination Truck, Gasoline
- Ocean Freighter, average fuel mix
- Ocean Freighter, Diesel
- Ocean Freighter, Residual Fuel Oil
- Train, Diesel.

Pavement specific means of transportation have been added using EPA emission factor in combination with UCPRC eLCAP truck types and diesel consumption per mile based on 2018 California statistics from the EMFAC2017 (v1.0.2) Emissions Inventory which have been combined with EPA emissions factors used for equipment:

- End Dump Truck, Diesel
- Transfer Truck, Diesel
- Ready Mix Concrete Truck, Diesel
- Concrete End Dump Truck
- Single Bottom Dump Truck, Diesel
- Double Bottom Dump Truck, Diesel
- Water Truck, Diesel
- Tack Truck, Diesel
- Spray Truck, Diesel

FUELS

Outreach for fuel data has identified the following datasets included in the tool, representing fuels:

Source: National Renewable Energy Laboratory

- Anthracite Coal, combusted in industrial boiler
- Bituminous coal, combusted in industrial boiler
- Diesel, combusted in industrial boiler
- Diesel, combusted in industrial equipment
- Gasoline, combusted in equipment
- Lignite coal, combusted in industrial boiler
- Liquefied petroleum gas, combusted in industrial boiler
- Natural gas, combusted in industrial boiler
- Natural gas, combusted in industrial equipment
- Residual fuel oil combusted in industrial boiler.

ELECTRICITY

Outreach has identified the following datasets included in the tool, representing electricity. The tool is making use of data for electricity from National Energy Technology Laboratory (NETL). Consumption-based data is used as opposed to production-based data to represent the actual use by processes. The US electricity baseline life cycle inventories are available through the Federal LCA Commons regionalized at the level of Balancing Authorities (BA).

DATA AVAILABILITY

Work is ongoing to identify other potentially publicly available datasets for LCA applications produced by the Federal government that could be available but are not currently included in the tool. The background datasets currently used in the LCA Pave tool have been compiled into a single repository named MTU/FHWA and is available in OpenLCA JSON-LD format through the Federal LCA Commons platform. It has the following life cycle inventories, compliant with the Federal Elementary Flow List (FEDEFL).

- USLCI background data: fossil fuels and transportation.
- NETL US Electricity Baseline (granularity: balancing authority, use consumption inventories)
- US EPA equipment inventories
- Asphalt binder life cycle inventories
- LCA frameworks for asphalt and concrete mixtures
- Various EPDs of relevant construction materials available publicly
- US EPA end-of-life construction and demolition LCI (in the process of updating)
- Impact Assessment Methods used to calculate the mid-point indicators.
  - FEDEFL compliant TRACI 2.1

- Cumulative Energy Demand

This repository is constantly being updated with the most recent publicly available life cycle inventories as well as datasets developed and made available for public use by industry.