LIFECYCLE INVENTORY

GOAL

Incorporate energy and emissions information into the decision-making process for pavement design alternatives.

REQUIREMENTS

Complete a lifecycle inventory for the final pavement design alternative for the project using the software tool, PaLATE v2.2 as modified for Greenroads, or approved equal. Report only results for total energy use and global warming potential (GWP) (in carbon dioxide equivalent emissions, CO_2e) for the final pavement design alternative. The following input values are required for PaLATE v2.2:

- **Total weight and types of virgin materials.** This includes aggregates, binders, base materials, and structures. These amounts can be design estimates or constructed totals.
- **Total weight and types of recycled materials.** PaLATE v2.2 models emissions and energy for several types of materials.
- **Expected transportation distances for all materials.** This means distances from source to production as well as from production to site. Transportation of waste to disposal is also included.
- **Expected construction vehicle types.** These include, but are not limited to, pavers, mixers, hauling vehicles, excavators, rollers, and finishing equipment.
- **Estimated design life.** Use the same input data as used in the PR-2 Lifecycle Cost Analysis.
- **Scheduled years and expected type of maintenance.** Use the same input data as used in the PR-2 Lifecycle Cost Analysis. This information should also match the project specifications provided to meet the requirements for PR-9 Pavement Maintenance Plan and PR-10 Site Maintenance Plan.

Details

There are several built-in limitations to the PaLATE tool, which are discussed in detail in the modified tool documentation. We recommend use of this tool because we are aware of these limitations, we have checked (or modified) the data sources, we know that the software reports the two requested pieces of information reliably for both asphalt and concrete pavements (even with a variety of recycled materials), we find it relatively easy to use, and we have modified the tool to meet Greenroads informational needs. The tool is available on the Greenroads website (http://www.greenroads.us) for download.

There are a few other software tools that are available for developing lifecycle inventories, both free and proprietary. These tools are also acceptable if they are able to produce energy use and GWP outputs and use a transparent interface that clearly references data sources used to compute these values.

DOCUMENTATION

- A copy of the input/output page for PaLATE v2.2 for Greenroads. If other software is used, provide a list of data sources in addition to the input list and output values for total energy use and GWP.

PR-3

REQUIRED

RELATED CREDITS

- ✓ PR-2 Lifecycle Cost Analysis
- ✓ PR-9 Pavement Management System
- ✓ PR-10 Site Maintenance Plan
- ✓ MR-1 Lifecycle Assessment

SUSTAINABILITY COMPONENTS

- ✓ Ecology
- ✓ Equity
- ✓ Extent
- ✓ Expectations
- ✓ Exposure

BENEFITS

- ✓ Improves Accountability
- ✓ Increases Awareness
- ✓ Creates New Information

APPROACHES & STRATEGIES

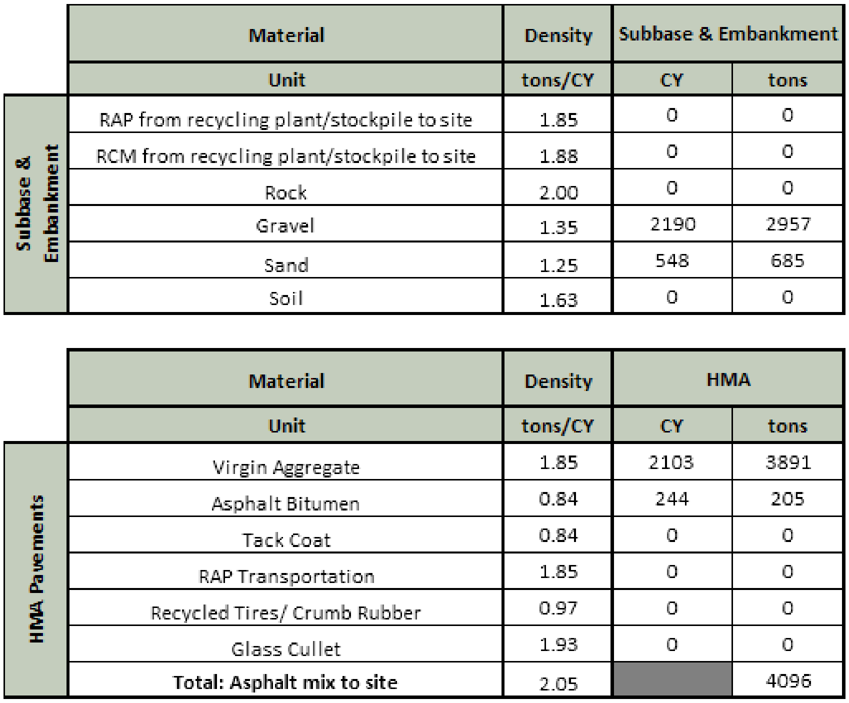
- Use PaLATE v2.2 for Greenroads as modified by the University of Washington. The tool is available in Microsoft Excel 2003 and 2007 format on the Greenroads website at: http://www.greenroads.us. All limitations and modifications made by Greenroads have been detailed in the supporting worksheets within the tool itself.
- Provide a list of data sources if not using PaLATE v2.2 as modified for Greenroads.
- Download a copy of the original version of PaLATE and modify it for use on your project and future projects. The original PaLATE tool, created in 2003 by the Consortium of Green Design at the University of California, Berkeley, is available in Microsoft 2003 format from the Recycled Materials Resource Center at the University of New Hampshire here: http://www.recycledmaterials.org/Resources/CD/PaLATE/PaLATE.xls. We know the limitations of this tool and know how it works, and may be able to assist you in modifying the tool to correct some of the known errors that could impact the outcome of your project LCI (such as double-counting and material densities).
- Use process-based data from the free National Renewable Energy Laboratory (NREL) LCI database, emissions factor and fuel use data from the Environmental Protection Agency (EPA) and the Department of Energy (DOE), and follow the LCI process methodology outlined by the International Standards Organization (ISO) 14040 and 14044 to complete a process-based LCI for the final pavement section.
- Use economic input-output data in the customizable, free tool for Economic Input/Output Life Cycle Assessment (EIO-LCA) from the Green Design Institute at Carnegie Mellon University. However, this tool does not allow for inclusion of project-specific process data. The EIO-LCA tool, including guidance on how to use the tool, is available at http://www.eiolca.net. EIO-LCA is the basis of the PaLATE tool, so the guidance document may be helpful in developing an initial understanding of how the model works.
- Use new software tool CHANGER (Calculator for Harmonised Assessment and Normalisation of Greenhouse-gas Emissions for Roads), which has been specifically designed for roadways by the International Road Federation (IRF). This software is not free, but is available for download from the IRF at: http://www.irfnet.org/.
- Do not use lifecycle assessment tools that are available for buildings to construct the project LCI model for the roadway project. There are several of these tools available, however they do not include enough process data about roadway materials or associated construction equipment to present results that are meaningful to roadways and are often of questionable validity and relevance.
- Consider hiring a consultant with experience in lifecycle assessment (LCA) and involve them in project development. This approach may be useful in simultaneously meeting the credit requirements for Credit MR-1 Lifecycle Assessment. The benefits of this approach include a full, project-specific review of environmental emissions impacts that extends the scope past reporting CO2e and energy, all of which may be used to make a more informed decision about project design alternatives. LCA experts or firms may also have access to proprietary data and software which may produce a more accurate, comprehensive, and project-based models due to higher overall data quality and fewer data gaps. Additionally, there is less likelihood of double-counting.

Example: Sample PaLATE v2.2 Results

This example represents a fictitious 12-inch, 12-foot wide lane of asphalt pavement section with a 12-inch deep and 14 foot wide gravel subbase, comprised (by volume) of 80% gravel and 20% sand with an assumed design life of 15 years. This example uses typical production process and construction equipment and the default densities for all materials. It is also assumed that asphalt is 5% by weight of the final HMA mixture. Note that this is an unrealistic example of an LCI because it does not include transportation, maintenance or demolition for simplicity. It is only representative of the construction phase of the roadway.

Table PR-3.1 shows the input values used for PaLATE v2.2 on the “Construction” worksheet page. Output values, from the “Results” worksheet page, are shown in Table PR-3.2.

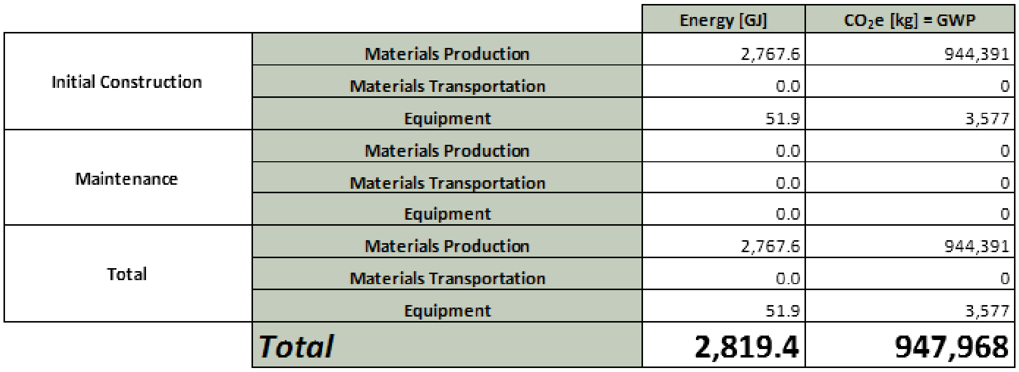
Table PR-3.1: PaLATE v2.2 for Greenroads input from "Construction" worksheet page.



	Material	Density	Subbase & Embankment	
	Unit	tons/CY	CY	tons
Subbase & Embankment	RAP from recycling plant/stockpile to site	1.85	0	0
	RCM from recycling plant/stockpile to site	1.88	0	0
	Rock	2.00	0	0
	Gravel	1.35	2190	2957
	Sand	1.25	548	685
	Soil	1.63	0	0

	Material	Density	HMA	
	Unit	tons/CY	CY	tons
HMA Pavements	Virgin Aggregate	1.85	2103	3891
	Asphalt Bitumen	0.84	244	205
	Tack Coat	0.84	0	0
	RAP Transportation	1.85	0	0
	Recycled Tires/ Crumb Rubber	0.97	0	0
	Glass Cullet	1.93	0	0
	Total: Asphalt mix to site	2.05		4096

Table PR-3.2: PaLATE v2.2 output table from "Results" worksheet page. Zero values mean not computed.



		Energy [GJ]	CO_2e [kg] = GWP
Initial Construction	Materials Production	2,767.6	944,391
	Materials Transportation	0.0	0
	Equipment	51.9	3,577
Maintenance	Materials Production	0.0	0
	Materials Transportation	0.0	0
	Equipment	0.0	0
Total	Materials Production	2,767.6	944,391
	Materials Transportation	0.0	0
	Equipment	51.9	3,577
	Total	**2,819.4**	**947,968**

Notes on the PaLATE v2.2 Data Sources

PaLATE v2.2 for Greenroads uses data from 2002 EIO-LCA producer data set and updated energy data for transportation modes from the 2009 Transportation Energy Data Book, available from the U.S. Department of Energy. However, this example is highly oversimplified and only intended to demonstrate the amount of information needed to document this Project Requirement. The transportation input data and maintenance data has been left out of this example model, and the input cells and rows for many of the material options and transportation modes have been hidden for simplicity and to limit image size. The output results show 0 for these phases and materials, and does not represent any emission from vehicle emissions in transportation, except as built into the sector data used.

PaLATE v2.2 uses the EIO-LCA data (http://www.eiolca.net) to make an asphalt pavement model. The model is built assuming the following materials are required to make asphalt: bitumen, virgin aggregate, gravel, and sand. The first is represented by the EIO-LCA sector called “asphalt paving mixture and block manufacture,” while the last three are from the “sand, gravel and clay refractory mining” sector. The differences between the last three are the densities. Basic emissions data for these three particular types of material is assumed to be the same even though the amount of processing (and thus energy and emissions) required to make these materials is realistically slightly different. Also, HMA plant production process data has been modified from the original PaLATE to be process based on data from the EPA AP-42.

The EIO-LCA database appears to use the Intergovernmental Panel on Climate Change (IPCC) 2nd Assessment Report (SAR) in 1996 to compute the index for Global Warming Potential based on CO_2e, though this is not explicitly stated. Note that the IPCC published revised values for greenhouse gas emissions in 2007 (see Solomon et al.). It is unclear if and when these new values will be incorporated into the EIO-LCA database; however, this detail is irrelevant to the intent of this Project Requirement and is likely to be only slightly higher or lower than the value computed.

Additionally, there are several limitations built in to a model that uses a pre-existing framework. Of particular importance is the potential for missing data where CO_2e or energy use is not recorded or otherwise measured, especially when taken as representative of an entire economic sector, because these missing data are hidden in the aggregated totals and are difficult to identify on a process level. The EIO-LCA assumptions and limitations regarding the economic sector energy and emissions model are cited in detail at:

- EIO-LCA Assumptions and Uncertainty: http://www.eiolca.net/Method/assumptions-and-uncertainty.html
- EIO-LCA Model Limitations: http://www.eiolca.net/Method/Limitations.html

References used for the original PaLATE data sources, as well as the data and modifications that have been made to the tool by the University of Washington, are documented in the tool itself.

POTENTIAL ISSUES

1. A simplified LCI, such as the one required here, is not intended to dictate final project decisions made. Instead, it is intended to inform the decision-making process through use of basic environmental accounting.
2. This Project Requirement requires reporting only two values for only one design alternative. The reason for this is that these two values are not generally considered in traditional roadway project planning or decision-making. However, in general, more than one alternative may be considered (and compared), and several types of emissions may also be pertinent to the decision-making process. We feel that requiring only the final design option is as a small step toward this comparison process, but could lead to more thoughtful accounting for multiple decision options in the future.
3. PaLATE investigations are limited to the pavement section and structures only. This includes base and subbase materials, and also recycled material options, but does not include other elements of the roadway environment.
4. Operational emissions due to vehicular traffic are also not considered in either version of PaLATE. These are, however, addressed elsewhere in Greenroads, because a different software tool is recommended for this modeling. See Credit AE-4 Traffic Emissions Reduction.
5. We believe that the EIO-LCA sector model used in the modified PaLATE v2.2 for Greenroads reports GWP based on outdated values assigned by the Intergovernmental Panel on Climate Change (IPCC) in 1996, instead of the more current 2007 values. Documentation regarding this issue is unclear. This means values output from PaLATE v2.2 can only be compared to other values output from PaLATE v2.2. Direct comparisons to other software tools, without a thorough investigation or review of their underlying assumptions or uncertainties, are therefore not valid.
6. Sector emissions and energy reported for the EIO-LCA data used in the modified version of PaLATE include feedstock emissions and energy from the extraction process of petroleum products and cement products (represented as a percentage of the total contribution to the cost for the streamlined processes modeled).
7. Technically, a full lifecycle assessment (LCA) is a much more involved and detailed process than a simple software-based lifecycle inventory (LCI) model can include. LCA involves additional considerations outside the pavement section alone and is highly dependent on quality, availability and relevance of data. Additionally, an impact assessment step is included in LCA which is not necessary for LCI. Impact assessment involves assigning

valuations and weights to certain outputs from the LCI. For this reason, credit is awarded for a full LCA in Credit MR-1 Lifecycle Assessment.

8. Economic lifecycle assessment models based on capital and lifetime maintenance costs do not typically include considerations of energy or emissions. However, lifecycle cost models are equally important and are covered under Project Requirement PR-2 Lifecycle Cost Analysis.
9. Similarly, social impacts can be measured using certain common metrics and indices that are intended to represent quality of life, health, or other equity-related, human-centric issues (such as birth and death rates or productivity rates). These are not well-researched and few systematic approaches have been refined well enough for incorporation into the lifecycle decision-making process requirements for Greenroads projects. The utility of applying these global metrics and indices on a project level are also not well understood or documented. However, the environmental review process (see PR-1 Environmental Review Process) addresses social impacts on a project-level.
10. The example leaves out transportation and maintenance on purpose. It should be understood that its simplicity is meant to demonstrate a process task; it is clearly not meant to be scaled by simple multiplication by the total mileage of the project. Each project will, and should be, different and none will match this example. This is also why both the input and output values are required for review.

RESEARCH

Lifecycle assessment (LCA) can be a useful decision-making tool for benchmarking roadway environmental performance (Schenck, 2000; Keoleian & Spitzley, 2006; Cooper & Fava, 2006) and as a method of environmental accounting for roadway systems. This particular requirement is the last part of a series of three related Project Requirements, which also include PR-1 Environmental Review Process and PR-2 Lifecycle Cost Analysis. This requirement focuses on developing a project-specific environmental accounting inventory (a lifecycle inventory: LCI) to aid in the decision-making process and also establishes baseline environmental performance (specifically energy use and carbon dioxide emissions) for the roadway pavement section. Project costs and social implications are addressed in prior requirements PR-1 and PR-2. A diagram of the main processes in a generic pavement lifecycle is provided in Figure PR-3.1 (next page).

A more detailed discussion of some of the finer details and types of LCA methodology is provided in the Research section of Credit MR-1 Lifecycle Assessment. This section introduces LCA and LCI and provides a review of existing literature for roads.

What is Lifecycle Assessment?

Lifecycle assessment (LCA) is a standardized, comprehensive tool that can be used for analyzing and quantifying the environmental impacts and sustainability of a product, system, and/or process. The International Standards Organization (ISO: 2006a) states that LCA is a process that “addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product’s life cycle from raw material acquisition, through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave).” Effectively, the “product” for this Greenroads requirement is the entire roadway project system.

LCA is a tool that can provide perspective on many elements of a system, effectively linking the production of a material to its use (Keoleian & Spitzley, 2006). In engineering applications, LCA offers a holistic, systems-based approach to project development and project management. It is often employed as a method of developing process alternatives. A lifecycle perspective necessitates a unique, and often unconventional, management strategy to optimize performance of materials, supply-chains, and to minimize or eliminate polluting activities.

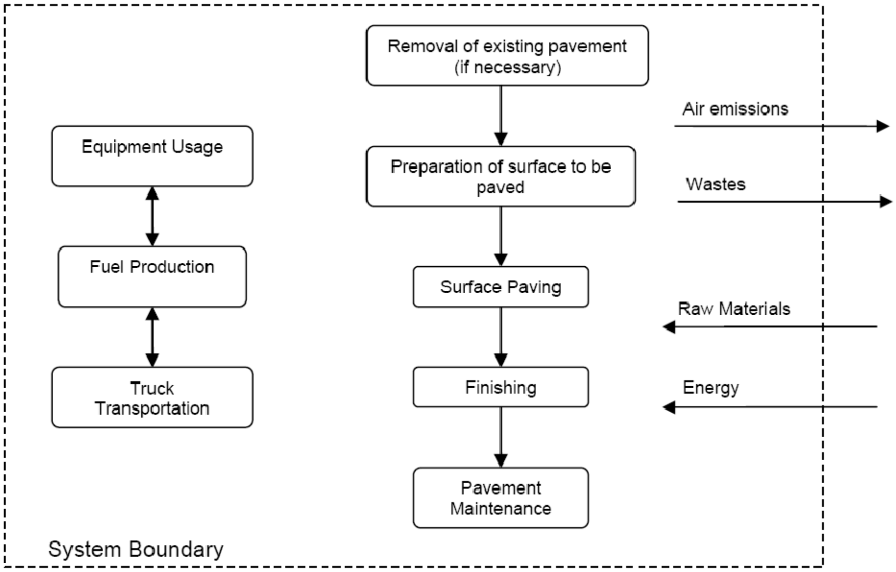


Figure PR-3.1: Basic lifecycle activities and system diagram for typical pavements. (Weiland, 2008)

Life cycle assessments have four stages (or phases) which are often iterative. These are shown graphically in Figure PR-3.2 and described below.

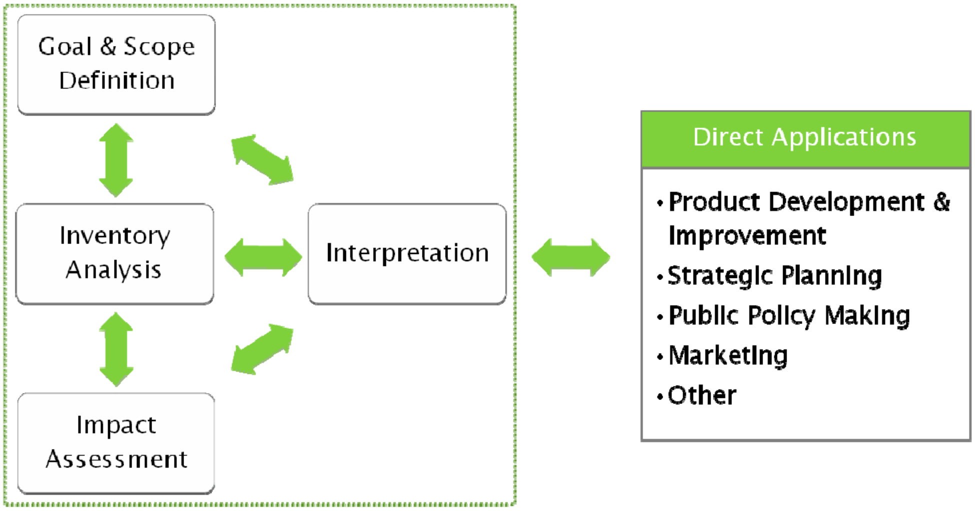


Figure PR-3.2: Stages of Lifecycle Assessment (Adapted from ISO, 2006a; ISO, 2006b)

- **Goal and Scope.** Specifying the goal of the project LCA documents the intended application, referenced literature for the project, intended audience (here the Greenroads review team), and proprietary status of final results. It also defines what thing or process will be studied and how much will be produced by the model. The most important part of this step comes with defining the system boundaries and identifying the processes and emissions to be included in the final outcome. Additionally, this section identifies some key limitations and assumptions of the model (specifically, what was scoped out, what processes were simplified and how they were estimated). Since the LCA process is iterative, it is crucial for the project team to develop a well-defined goal and scope in order to have a meaningful end product.
- **Lifecycle Inventory Analysis (LCI).** The 2006 ISO14044 Standard Section 4.3 provides the basic background and procedures required for life-cycle inventory analyses based on the functional units and reference flows defined in the Goal and Scope. A functional unit is defined as the “quantified performance of a product system for use as a reference unit.” A reference flow is the “measure of the outputs from processes in a given product system

required to fulfil [sic] the function expressed by the functional unit." The alternatives under comparison for the inventory analyses are then described with reference to their specific unit processes and functional units. Each alternative will likely be comprised of slightly different processes. The purpose of the inventory analysis is to produce both qualitative and quantitative information and refined definitions of the unit processes within the system boundaries. The inventory analysis procedure consists of data collection, data processing and calculations, and allocation of environmental flows and releases, such as emissions, energy use, water, fuels, and other materials or byproducts that were specified in the Goal & Scope for the project.

- **Lifecycle Impact Assessment (LCIA).** The 2006 ISO14044 Standard Section 4.4 provides the basic background and procedures required for lifecycle impact assessments (LCIA) based on the functional units and reference flows defined in the Goal and Scope. Impact assessment uses the results of the inventory analysis to identify impacts associated with the emissions and material flows. Impacts must be classified and characterized according to the ISO14044 Standard (2006b). Usually this involves assigning equivalency factors to the inventory data (e.g. a conversion factor) to produce an aggregate indicator value that can be compared to another impact index, known metric or industry average. LCIA is typically used for comparing two or more products with the same functional unit.
- **Interpretation.** The last phase of the LCA is interpretation and presentation of the results. "The first step in decision analysis is to identify all important objectives and attributes. While this step may seem obvious, it is necessary to ensure that the valuation focuses on the right problem." (EPA, 2000) The FRED documentation provides additional guidance and suggestions for decision-making based on LCI and LCIA results, such as:

  - Adopting an existing decision-making weighting scheme.
  - Using the Analytical Hierarchy Process (AHP).
  - Using the Modified Delphi Technique.
  - Using a Multi-Attribute Utility Theory.

However, for this Project Requirement, neither the LCIA nor the interpretation steps are required. This Project Requirement focuses on one component of the LCA, the lifecycle inventory (LCI) analysis. The purpose of the inventory analysis is to collect various data on inputs and outputs of the system relevant to the goals of the study and within the defined boundaries of the study (ISO, 2006a) Thus by default, the LCI will also require a well-refined and clear goal statement and scope of assessment. Approaches to refining the goal and scope are not discussed here. Please see the research section of Credit MR-1 Lifecycle Assessment. Both LCI and LCA can be used in a more informed decision-making process (ISO, 2006a; Schenck, 2000).

LCI and LCA studies are similar, but cannot be compared unless the context of assessment is the same. ISO (2006a) states, "LCI studies are not to be confused with the LCI phase of an LCA study." Similarly, LCA and LCI are not to be confused with conventional lifecycle cost analysis (LCCA). LCCAs are frequently mistaken for the process-based and streamlined methods of life cycle assessment. LCCA is actually an approach used in what is typically termed "engineering economics" (a misnomer, for there is very little of either engineering or economics involved) which allows determination of past, present and future values of a variety of initial capital and long-term inputs and outputs based on cost alone, compounded over time. Additionally, LCCAs rarely systematically account for end-of-life costs, such as disposal fees or recycling costs, because these are difficult to estimate. While all methods are based on a similar timelines (the whole lifecycle), they each have fundamentally different outputs and resulting implications for the design process, and therefore different utility in decision-making. PR-2 discusses LCCA in detail.

LCA and Sustainability Benefits

Keoleian & Spitzley (2006) suggest that "Life cycle based sustainability models and metrics play a key role in guiding the transformation of technology, consumption patterns, and corporate and governmental policies for achieving a more sustainable society." An LCA approach can be used in many applications. Some of the most often cited are noted below:

- Lifecycle models promote an awareness of production effects and connect them to use or consumption of a system or process.

- Setting lifecycle boundaries at a system level allows for comprehensive environmental, social and economic accounting metrics to be used in a meaningful way to measure and monitor performance.
- Lifecycle metrics inform decision-makers and can be used by stakeholders to manage and assess the system or product (Keoleian & Spitzey, 2006).
- LCA can help identify "opportunities to improve environmental performance of products at various points in their lifecycle." (ISO, 2006a)
- LCA can help inform the industry decision-makers, government agencies and policy-makers for strategic planning, performance benchmarking, or product development and redesign. (ISO, 2006a)
- LCA can help evaluate the relevance of various indicators for environmental performance (ISO, 2006a).
- LCA provides a marketing opportunity such as eco-labeling and declarations of environmental performance (ISO, 2006a).

A survey completed by Cooper and Fava in 2006 shows that LCA is widely used for a number of applications. Table PR-3.3 summarizes the results, by percentage of respondents.

Table PR-3.3: Prevalence LCA Use by Practioners (Adapted from Cooper & Fava, 2006)

Use of LCA	Response
Business strategy and planning	63%
Product and system research and development	62%
Inputs for design (products or processes)	52%
Education	46%
Policy development	43%
Marketing schemes (labeling, environmental declarations)	37%
Sales	26%
Procurement	20%
Other (including bidding or tender packages)	8%

Types of LCAs

In general, there are three or four types of LCA models depending on the source of information. One type is the Economic Input-Output model (EIO) for Life Cycle Assessment (EIO-LCA). For example, this Project Requirement is based on an EIO-LCA model (http://www.eiolca.net). Second is a process-based LCA, which follows a standard methodology set forth by the International Standards Organization (ISO) 14040 and 14044 for Lifecycle Assessment. This method, also called ISO-LCA (Cooper & Fava, 2006), often produces more detailed results than the EIO-LCA model (Hendrickson, Lave & Matthews, 2006). Process-based LCAs involve project-specific process data and generally use a computational tool or matrix analysis to form a model and complete the assessment of data, such the method outlined by Heijungs and Suh (2002). There also is a third method of life cycle assessment, which is recently becoming more prevalent called Hybrid LCA, where an EIO model is supplemented by or integrated with process-based data to produce a more comprehensive representation of the environmental effects of the system processes. These are discussed in further detail in Credit MR-1 Lifecycle Assessment.

Modifying any of these three LCA methodologies may result in what is called a "streamlined LCA;" while not a specific class or type of LCA, a streamlined LCA strategically omits or simplifies the LCA method to make it less computationally intensive, such as through the creation of a software tool (Weitz, Todd, Curran & Malkin, 1996) that deliberately leaves out collection of some types of data or a particular impact assessment. The PaLATE v2.0 for Greenroads is an example of a streamlined EIO-LCA tool. There are a number of different streamlined tools available for roads which vary in LCA methodology (i.e. streamlined ISO-LCA tools). In addition to the PaLATE tools originally developed by Horvath et al. (2003):

- Huang et al. (2008, 2009) has developed a Microsoft Excel tool for streamlining pavement LCAs and system modeling (based in the United Kingdom)

- Birgisdóttir (2005), Christensen and Birgisdóttir (2006), Birgisdóttir et al. (2007) describe the development of the Danish ROAD-RES software tool for that incorporates municipal solid waste incinerator residues in pavement LCAs.
- Apul et al. (n.d.; Apul, 2007) at the University of Toledo developed a web-based tool for LCA called BenReMod-LCA (Beneficial Reuse Modules). An extension of this tool, as a multi-criteria decision-making tool, BenReMod-MCDA, is currently under development by the same authors. Both tools are available at: http://benremod.eng.utoledo.edu/BenReMod/
- CHANGER (the Calculator for Harmonised Assessment and Normalisation of Greenhouse-gas Emissions for Roads), a paid software tool, recently became available for modeling greenhouse gas emissions from pavements for from the International Road Federation (IRF, 2010). CHANGER includes data sources for 188 countries and global and regional income groups (IRF, 2010).

Each of these streamlined tools has drawbacks due to various built-in assumptions and limitations. Most commonly these tools suffer from double-counting errors, poor or very poor data quality, lack of transparency, data omissions and general user-unfriendliness. This means they may not produce reliable or meaningful results that accurately or precisely reflect roadway lifecycle impacts.

It is unlikely a process-based LCI will produce results that match of a streamlined LCI model or an EIO-LCA model. This is due to issues with data quality and the scope of the EIO models and their general lack of process-specificity to particular processes within a system. Thus, it is also unlikely that the inventory data produced for PR-3 will match the results of the Process-Based LCA or Hybrid LCA required for the Credit MR-1.

Existing Roadway LCAs

The weight of any Voluntary Credit in Greenroads v1.5 that involves materials, construction, transportation from construction and traffic use, was determined by a thorough review of existing lifecycle assessment literature for roads. We used the literature review process in attempt to identify patterns for typical LCA results for LCAs that used a transparent, systematic approach to evaluate the pavement section and reported the total energy use or total CO_2 (or CO_2e). Each document reviewed (there are, to date 13 papers with 45 different real or hypothetical road types). (Athena Institute, 2006; Carpenter et al., 2007; Chui et al., 2008; Horvath, 2003; Huang et al., 2009a; Huang et al., 2009b; Mroueh et al., 2001; Rajendran & Gambatese, 2007; Schenck, 2000; Stripple, 2000; Stripple, 2001; Weiland, 2008; Zapata & Gambatese, 2005) For more information on how the weighting decisions were made, please refer to the introduction of this manual or to Muench & Anderson (submitted for publication). We used a systematic, lifecycle-based approach to determine their overall credit weight on a five point scale, with some concessions, which are explained in Muench & Anderson.

Types of Investigations

Five papers addressed PCC pavements (10 assessments), while all 13 address HMA pavements (36 assessments). Note that Schenck (2000) addressed resurfacing maintenance only, and her results are not included in the following figures or tables. Figure PR-3.3 (next page) shows the described pavement structure for each studied assessment (12 papers, 43 total). Each author used different data sources and defined their system boundaries differently. However, a basic statistical analysis shows that there are some noticeable general trends on a per lane-kilometer basis of the 43 LCA studies. These trends include similarities in the scope of the study (pavement section only), results on energy use and CO_2 production, and a contribution analysis of the energy and CO_2 attributable according to each lifecycle phase of the roadway. We used median values to limit influence of extreme outliers in the data.

The scope and boundaries of most papers (10 assessments) examine only the pavement structure and exclude other elements of the roadway. Stripple (2001), however, completed the only full life cycle inventory that included other roadway activities and material needs, like land-clearing, electric utilities, and signs. This paper is discussed in further detail in Credit MR-1. The phases typically considered in the scope of the assessments are initial construction and pavement-related maintenance activities over a general range of assumed design lives between 40 to 50 years. Two papers also included vehicle emissions from traffic during the operation and use of the completed roadway (Stripple, 2001; Kennedy, 2006).

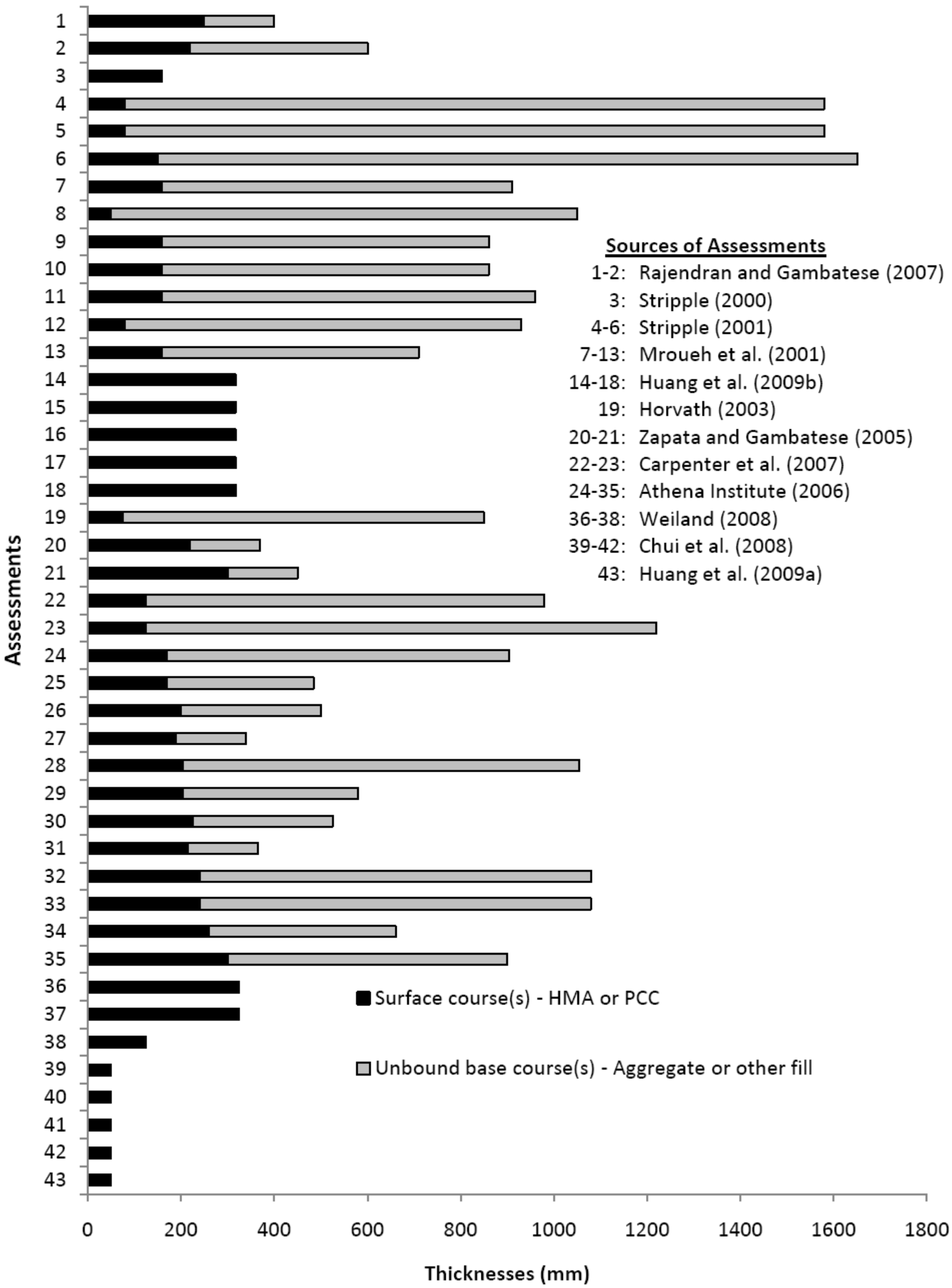


Figure PR-3.3: LCA assessments and their studied pavement structures. (Muench & Anderson, Submitted)

Energy Use

Total energy use was reported by 35 assessments, and the distribution in ranges of terajoules (TJ) is shown in Figure PR-3.4. The median result is approximately 3.17 TJ per lane-km. The study by Horvath (2003) represented the extreme outlier, reporting an energy use of 17.25 TJ per lane-km (10.72 TJ per lane-mile). This is the only study that uses the EIO-LCA model and the original version of the PaLATE software, which is recommended in modified form for completing this Greenroads Project Requirement. A review of the original PaLATE software indicated that there are several errors in key cost and emissions values, which in our opinion renders this number (but not the method) suspect. A reasonable approximation of the total energy expenditure attributable to one typical lane-km of pavement is 2-4 TJ, which varies slightly depending upon the pavement structure and material. In 2005, the average annual American residential household energy use was 0.1 TJ (94.9 million BTU: Energy Information Administration, 2009). This means one lane-km of roadway uses the same energy as 20-40 households do in one year. To put this in more familiar U.S. measures of roads: the median energy use of one mile of road represents the average energy use of 51 homes in one year, with the range of energy consumption representing that used by between 32-64 homes a year.

DID YOU KNOW?

The median energy use by one lane, one mile long, of road pavement represents the same energy use that about 51 average U.S. households use in one whole year.

How many households does it take you to drive to work?

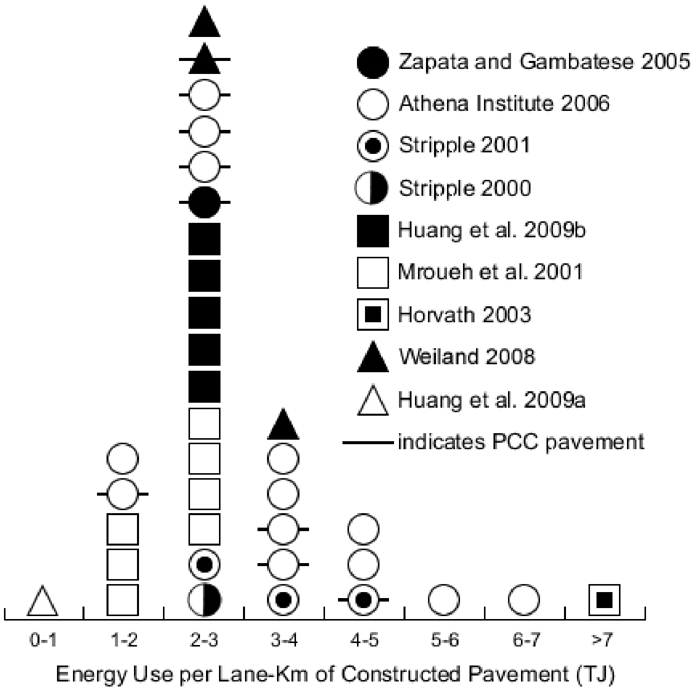


Figure PR-3.4. Distribution of energy use in pavements for 34 assessments in 9 pavement LCA papers. Each symbol represents one assessment. (Muench, Anderson, Submitted)

Carbon Dioxide (CO_2) Emissions

Six papers reported total CO_2 emissions from a total of 19 assessments and one paper reported global warming potential (expressed in CO_2e) rather than CO_2 only emissions on another 12 assessments (31 total). It is unclear if the first six papers were reporting CO_2e or only CO_2; however, this would not significantly influence the statistical results either way. The results show a median value of 243 metric tons (MT) per lane-km, though the distribution had higher variability than the results for energy use. The histogram is shown in Figure PR-3.5. The highest values were cited in the papers by Stripple (2000 and 2001) which included aspects of road construction outside the primary road structural materials and construction activities. Therefore, a reasonable approximate range of the total CO_2 emissions that is attributable to one typical lane-km of pavement is 100-500 MT, which varies slightly depending upon the pavement structure and material, and also the scope of the LCA. One metric tonne of CO_2, at standard temperature and pressure, has a volume of about 729 cubic meters (Figure PR-3.6).

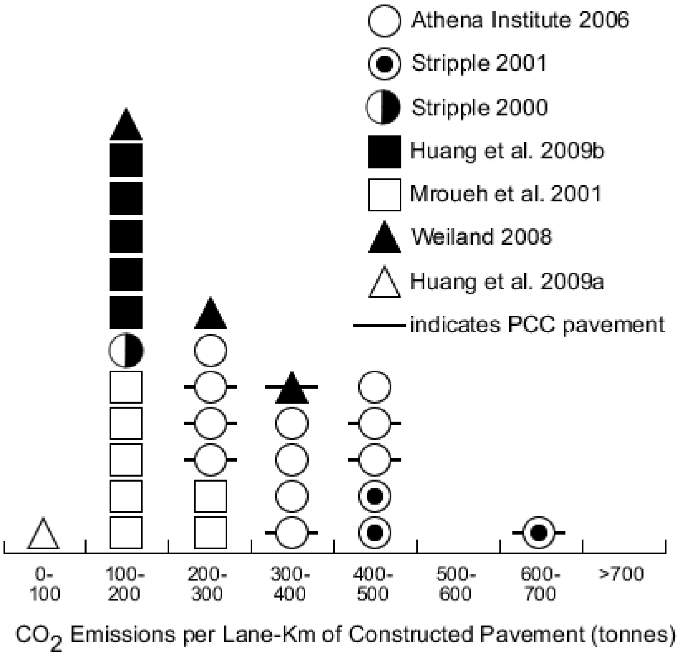


Figure PR-3.5. Distribution of CO_2 emissions in pavement for 32 assessments in 7 pavement LCA papers. Each symbol represents one assessment. (Muench, Anderson, Submitted)

Figure PR-3.6: One metric ton (MT) of CO_2 as modeled by a Massachusetts high school physics class. The cube is 27 feet per side. (http://www.energyrace.com/images/uploads/commentary/co2cube4.jpg)

Contribution Analysis of Lifecycle Stages

Several papers, as shown in Table PR-3.4 and Table PR-3.5, analyzed energy use and CO_2 emissions according to four major lifecycle stages or activities: materials production, pavement construction (initial and maintenance), and transportation associated with construction. The relative contributions of each stage or activity are reasonably consistent across the small number of studies. In general, materials production accounts for about 75% of energy use and 60-70% of CO_2 emissions; construction accounts for less than 5% of both energy use and CO_2 emissions; and transport of materials for production and during construction accounts for about 20% of energy use and about 10% of CO_2 emissions. Maintenance activities seem to account for about 25% of energy use and about 10-20% of CO_2 emissions when compared to initial construction.

Table PR-3.4: Relative Energy Contributions of Road Construction Lifecycle Stages (Adapted from Muench & Anderson, Submitted)

Lifecycle Stage	No. Papers	No. LCAs	Average (%)	Median (%)	St. Dev (%)	Range (%)
Materials Production	5	14	74	73	13	60-98
Construction	5	14	3	2	2	2-10
Transportation	4	12	21	21	11	7-38
Initial Construction	4	8	74	73	21	45-97
Maintenance	4	8	26	27	21	3-55

Table PR-3.5: Relative CO_2 Emission Contributions of Road Construction Lifecycle Stages (ibid.)

Lifecycle Stage	No. Papers	No. LCAs	Average (%)	Median (%)	St. Dev (%)	Range (%)
Materials Production	1	3	69	61	15	60-87
Construction	1	3	4	4	2	1-6
Transportation	1	3	8	9	3	4-10
Initial Construction	3	16	78	86	20	45-100
Maintenance	3	16	22	14	20	0-55

Based on these results, there are some general rules of thumb which are shown in Table PR-3.6.

Table PR-3.6: General rules of thumb for pavement energy and emissions (ibid.)

Comparison	Energy Use	CO_2 Emissions
Materials Production to Construction Processes	25 to 1	16 to 1
Transportation to Construction	8 to 1	3 to 1
Maintenance Activities to Initial Construction	1 to 3	1 to 4

A Note on Disposal, Use, and Operations Lifecycle Stages

Not included in the figures or tables above are three very critical lifecycle stages or activities: use (vehicular traffic), operations (such as lighting and signals), and the waste disposal process from demolished pavements. Rajendran and Gambatese (2007) attempted to quantify waste production processes throughout the roadway lifecycle, especially in construction. However, this is the only study that has done so. As noted in PR-6 Construction Waste Management Plan and by Rajendran and Gambetese (2007), there is very little information available about the generation or disposal of roadway waste products. Also, several authors investigated either a by-weight or by-volume approach to replacing pavement materials in-kind with different recycled materials (such as coal fly ash instead of cement) in order to reduce the lifecycle energy use or CO_2 emissions. These assessments, in general, are complicated to model because recycled materials generally came from another system that is outside the scope or the boundaries of the assessment. Introducing recycled materials into a new roadway project system or even reusing waste materials generated from the project itself represents a feedback loop, because the materials are reintroduced somewhere into a previous lifecycle stage along the system supply chain. It is therefore often difficult to disaggregate the environmental accountability and assign it to a responsible party when using recycled material. There are a variety of methods used, and again, each has its own assumptions, limitations, uncertainties, advantages and disadvantages.

Further, only one study (Stripple, 2001) investigated operations. In general, electrical equipment such as that used for signals and lighting contributed the most to energy use and CO2 emissions of all the operational components studied, (1) for rural environments, operations contributed almost negligibly for both energy and CO2, and (2) the energy mix used was based on Swedish power sources, which are mostly hydropower and nuclear energy.

Traffic use is rarely considered in pavement-based lifecycle assessments. However, two studies (Stripple, 2001 and Kennedy, 2006) model the impacts due to traffic use. If traffic is considered in the scope of the LCA, then vehicular emissions dominate the total energy consumption and carbon dioxide emissions. However, this is widely variable and depends a number of factors including (but not limited to) vehicle mix, modal access, fuel efficiency and type of fuel. Generally, the energy expended in construction is about the same as that expended by roadway users in the first two years of service. Typical pavement maintenance activities (overlays) generally use lower volumes of materials and this would represent a shorter timeline than one to two years.

Caveats of LCIs

Clearly, existing roadway LCIs and LCAs vary in method. Sometimes this variety lends to reporting contradictory or mixed results, which can be confusing, especially in a decision-making context. The effectiveness of LCI or LCA studies are highly dependent on the goal and scope definition, data sources and quality, model limitations and uncertainties. Additionally, many publicly available databases or completed LCIs often use or contain average information that cannot be easily applied in project-specific contexts. The converse is also true; project-specific LCIs should not necessarily become baseline models for other projects without thorough review of the variables that were considered. Thus results of the inventory are best used as a tool or a benchmarking method, but not as a baseline value. Another point that must be made expressly clear: completing a lifecycle inventory or a lifecycle assessment of your project does not, by virtue of the process or method alone, make a project more or less sustainable than another project.

Additional Resources

- The Carnegie Mellon Green Design Institute database is publicly available and free to use non-commercially. It also provides a very thorough explanation of the finer points of the EIO-LCA methodology as well as discussion and examples of the methodology. EIO-LCA is available at http://www.eiolca.net.
- The Society of Environmental Toxicology and Chemistry (SETAC) provides a thorough and concise description of the ISO-LCA methodology as well as links to other professional LCA resources and organizations. More information is available at http://www.setac.org/.

GLOSSARY

BenReMod	Beneficial Reuse Module
CHANGER	Calculator for Harmonised Assessment and Normalisation of Greenhouse-gas Emissions for Roads
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent emission
EIO	Economic Input-Output
EIO-LCA	Economic Input-Output for Life Cycle Assessment
EOL	End-of-life
Feedback loop	A process within a system where outputs of a process are reintroduced as inputs into a previous lifecycle stage somewhere along the same system supply chain
Functional unit	The quantified performance of a product system for use as a reference unit (ISO, 2006a)
ISO	International Standards Organization
ISO-LCA	Process-based LCA
LCA	Lifecycle assessment
LCCA	Lifecycle cost analysis

LCI	Lifecycle inventory analysis
LCIA	Lifecycle impact assessment
Lifecycle	consecutive and interlinked stages of a product [or project] system, from raw material acquisition or generation from natural resources to final disposal or [end-of life: EOL] (ISO, 2006a)
Lifecycle assessment	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle (ISO, 2006a)
Maintenance	Routine construction activities which are preservative in nature, such as patching and repair. Typically maintenance involves additional production of material as well as additional transport and construction activities. See also operations.
MCDA	Multi-Criteria Decision Analysis
Operations	Equipment, components or activities that are needed on a routine basis to ensure proper safety during use of a road, e.g. luminaires, signals, de-icing, striping, sanding, drawbridge mechanical equipment, toll booths, etc. (Muench & Anderson, submitted) See also maintenance.
PaLATE	Pavement Lifecycle Assessment Tool for Environmental and Economic Effects
Reference flow	The measure of the outputs from processes in a given product system required to fulfil [sic] the function expressed by the functional unit (ISO, 2006a)
SETAC	Society of Enviornmental Toxicology and Chemistry
System boundary	Set of criteria defining which unit processes are part of a system (ISO, 2006a)
Unit process	Smallest unit considered in the lifecycle inventory analysis for which input and output data are quantified (ISO, 2006a)

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