# CHAPTER 10. ASSESSING PAVEMENT SUSTAINABILITY

## Introduction

In general, there are four broadly categorized measurement tools, or methods, that are typically used either in isolation or in concert to quantify various aspects of sustainability: performance assessment, life-cycle cost analysis, life-cycle assessment, and sustainability rating systems. These methods were introduced in chapter 2 and are discussed in more detail here. Because performance assessment is a long-standing method of evaluation and is essentially built into current standards, it is not addressed in detail as a measurement tool. Notably, there are few, if any, generally accepted metrics able to measure equity/social impacts associated with pavement systems, although a few are recognized to some degree in sustainability rating systems.

***Pavement Sustainability Aspects Can Be Evaluated Using:***

- ✓ *Performance assessment.*
- ✓ *Life-cycle cost analysis.*
- ✓ *Life-cycle assessment.*
- ✓ *Rating systems.*

## Life-Cycle Cost Analysis (LCCA)

### Background

According to the Transportation Equity Act for the 21st Century (TEA-21), LCCA is "…a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment." Because LCCA is an essential component of most pavement type selection processes, many other definitions incorporate descriptions of typical LCCA applications (e.g., "LCCA is an analytical tool to provide a cost comparison between two or more competing design alternatives producing equivalent benefits for the project being analyzed" [NHI 2008]). However, whether used to compare competing alternatives or simply to assess the total expected cost of a single strategy, the basic analytical process remains the same. In simplest terms, LCCA can be considered to be a generally accepted accounting practice that "…offers sophisticated methods to determine and demonstrate the economic merits of the selected alternative in an analytical and fact-based manner" (FHWA 2013).

The basic pavement LCCA process requires that the analyst define the schedule of initial and future activities involved in implementing a specific alternative (whether new construction or rehabilitation). Next, the costs of each of these activities are estimated. The predicted schedule of activities and their associated costs comprise the projected life-cycle cost stream, an example of which is depicted in figure 10-1. Using an economic analysis technique known as "discounting," all projected costs are converted into present dollars and summed to produce a net present value (NPV) or net present cost (NPC). If multiple alternatives with similar benefits are being considered over identical analysis periods, the net present values or costs can be compared to determine which alternative is the most cost effective. More thorough descriptions of the LCCA process can be found in numerous publications (e.g., Walls and Smith 1998; Riggs and West 1986; FHWA 2002; FHWA 2004; NHI 2008; FHWA 2010; ACPA 2011).

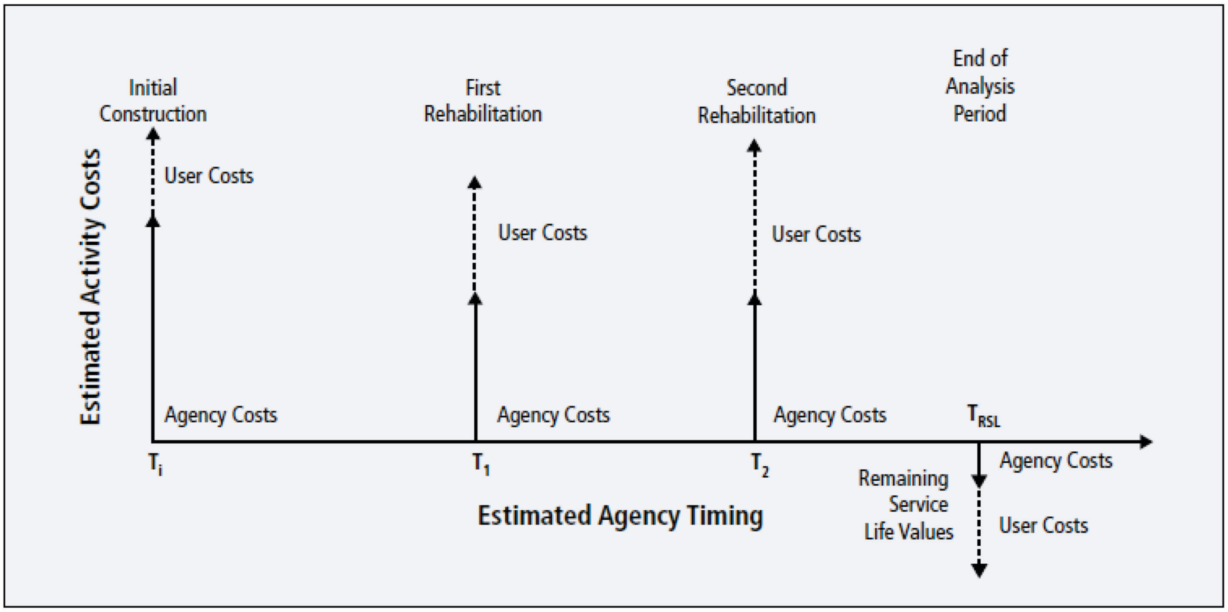



Figure 10-1. Example projected life-cycle cost stream diagram (FHWA 2002).

LCCA provides a means of measuring the economic consequences of design, materials, construction techniques, maintenance schemes, and end-of-life treatments. If the economic inputs for these are reasonable, LCCA is a tool that can account for their economic impact over the life cycle and is thus able to measure that component of sustainability.

Like most analytical tools, LCCA is not without limitations and, if used incorrectly, can provide false support for poor choices. While the accurate estimation of the timing and costs of life-cycle activities is the most important factor in conducting a good pavement LCCA (see Hallin et al. [2011] for guidance on developing reasonable maintenance and rehabilitation strategies), there are several additional considerations that are also important, as described in the next section.

## Key Issues in LCCA

As noted previously, LCCA is useful for determining the economic impact of potential changes in design, construction, materials, etc. that are intended to improve the environmental or societal impacts of a pavement project. NPV or NPC is also commonly used to select from among various design or rehabilitation alternatives that are believed to provide the same level of performance or benefits to the project's users during normal operations over the same analysis period.

If the benefits are the same but the analysis periods differ, then equivalent uniform annual cost (EUAC) analysis is useful in identifying the preferred alternative. Implicit in an EUAC analysis is the assumption that the strategies are repeated at the end of the analysis periods. An alternate approach (and the one that is recommended by FHWA) is to use the same analysis period (generally the shortest of those being considered) for all candidate alternatives and to include the remaining value of each alternative at the end of the analysis period (i.e., salvage value of materials or value of remaining service life) as a "benefit" or "negative cost" at the end of the analysis period.

If the benefits vary among the candidate alternatives (e.g., if they provide different levels of service), then the alternatives cannot be compared solely on the basis of cost and, consequently, LCCA alone may not be an appropriate means of comparison. If all benefits can be expressed monetarily, then the benefits can be considered in the same analysis as the costs, discounted similarly, and a decision can still be made based on the results of the analysis and the overall objective (e.g., to maximize net benefits or minimize net costs).

Another option for analyzing monetarily expressed costs and benefits that is sometimes favored by public agencies is benefit-cost analysis (BCA), in which the ratio of discounted benefits to discounted costs is computed. Unfortunately, simple BCA can lead to incorrect strategy selections in some cases, although incremental BCA, a more complex analysis, will yield consistently correct strategy selections (Riggs and West 1986). Because of its relative simplicity, NPV analysis is often preferred over BCA for economic analyses.

It must also be noted that, because there are usually other decision factors in the selection process that cannot be easily quantified monetarily (e.g., work zone safety, environmental impacts, impact of local development), LCCA alone is rarely sufficient for selecting from among competing alternatives. Utility theory and other forms of value engineering are sometimes useful in evaluating the preferred alternative when monetary and nonmonetary considerations must be balanced. In such cases, the option with the lowest LCC may not be implemented. Nevertheless, LCCA provides valuable information to the overall decision-making process.

The following subsections briefly describe additional considerations in the proper conduct of LCCA.

### *Discount Rate*

It is generally accepted that all future cost streams should be estimated in constant (current) dollars and discounted to present dollar values using a real discount rate, which represents the combined effects of interest and inflation rates. For pavement project LCCAs, the selected discount rate used should reflect both historical trends over long periods of time and near-term projections. The U.S. Office of Management and Budget (OMB) provides federal agencies with guidance concerning many of the technical aspects of conducting economic analyses, including the selection of a discount rate. FHWA recommends that highway agencies use OMB Circular A-94, Appendix C (OMB 2012) in selecting a discount rate, and many agencies use rates that are based on the "real interest rates on Treasury Notes and Bonds" found in that document, which is updated annually.

The choice of discount rate is very important and thus it is useful to understand the impact of discount rate on LCCA. Higher discount rates reduce the present value of future costs by a greater amount than do lower discount rates; a zero discount rate values future costs the same as current costs; and negative discount rates increase the present value of future costs above those of current costs.

### *End-of-Analysis (Residual) Value: Salvage Value vs. Remaining Service Life Value*

It is often necessary to assign a value (generally a benefit or negative cost) to the pavement at end of the LCC analysis period to capture either the value of the remaining pavement life (assuming that the pavement's service life has not been fully consumed at the end of the analysis period) or the "salvage" value of the materials that will be derived from the pavement structure if it will have no remaining service life (e.g., if the pavement is to be removed and replaced at the end of the analysis period). Alternatively, the "salvage value" may be computed as the value of the existing pavement as a support layer for an overlay at the end of the analysis period (i.e., recycling or "repurposing" the pavement in place).

These options are mutually exclusive for any given LCCA; that is, no analysis should include both a salvage value and a remaining service life value. Whichever end-of-analysis value is selected (if any), it should reflect what the agency realistically expects will be done with the pavement structure at the end of the analysis period. ACPA (2011) and West et al. (2012) provide summaries of U.S. state highway agency practices concerning the inclusion of salvage and remaining service life values in their LCCAs.

It should be noted that consideration must be given to the proper allocation of pavement salvage values to avoid "double counting" their contributions to the LCCA. For example, it may be appropriate to consider the value of salvaged materials as a positive cash flow at the end of the analysis period if the agency retains the ownership of the material for use on another project. In such cases, the salvage value might be considered to be equal to the cost savings associated with using the material on another project. On the other hand, if the contractor retains ownership of the material, then the agency receives no immediate benefit from the salvage operation and no benefit should be reflected at the end of the LCCA analysis period. However, it is reasonable to expect that the contractor will use the material on a different project and that the bid price for the material on that project will reflect the contractor's low cost in obtaining the material. In this way, the agency benefit for the salvage value of the old pavement should be reflected (at least partially) in the lower initial costs of future projects. In any event, it is extremely important that the analyst place the salvage value benefit of any given material at the end of the analysis period <u>or</u> as a reduction in cost at the beginning of the next project, but not fully in both places. If different materials from the same project are used in different ways, then portions of the salvage value may be allocated to both places.

### *User Cost Estimates*

User costs originate primarily from vehicle operating costs (i.e., vehicle wear and tear, fuel consumption, repairs and maintenance), delay costs (e.g., from increases in time required to travel between two points as a result of work zones, congestion, etc.), and crash costs (which are often a result of driver error and other factors not related to the roadway conditions and, as a result, are generally not factored into LCCA) (Walls and Smith 1998).

The value of road users' time is a subject of great debate. User delay costs are generally computed in consideration of vehicle class, trip type (urban or rural), and trip purpose (business or personal). Details concerning the computation of user costs can be found in NCHRP (2004), and free software for computing these costs is a part of the FHWA *RealCost* LCCA program (FHWA 2010) or the CA4PRS software (Caltrans 2011).

While there is no doubt that user costs should be considered in decision-making processes, it is widely recognized that these costs should not be included in the same LCCA cost stream as agency costs because: 1) although there is much literature on the topic, the quantification of user costs is subject to debate and uncertainty (FHWA 2002), 2) user costs "do not debit agency budgets as do agency costs" (FHWA 2002); and 3) computed user costs on some projects can be so large as to swamp the decision process or to drive it toward options that the agency cannot afford. Therefore, it is common for user costs to be weighted differently than agency costs in the decision process or (as current FHWA policy recommends) for user costs to be computed and analyzed separately from agency costs. The consideration of user costs in LCCA is described in more detail later in this chapter.

### *Deterministic LCCA vs. Probabilistic LCCA*

The use of fixed values for all LCCA inputs (e.g., activity timing, costs, discount rate) to produce a single output value is referred to as the *deterministic* approach to LCCA. While this approach is relatively simple and requires few inputs, it fails to adequately account for either the variability in actual initial costs and discount rates over time or the uncertainty in the timing and costs of planned maintenance and rehabilitation activities. Furthermore, the output of a single value (i.e., NPV or NPC) without some statement to qualify that value may imply a degree of certainty in the conclusion that is inappropriate (FHWA 2010). Sensitivity analyses (i.e., varying input values, often one at a time, and rerunning the analysis to determine how sensitive the output value is to variations in specific inputs) can give the analyst a better sense of confidence in the accuracy of deterministic LCCA results.

The *probabilistic* approach to LCCA is more realistic in that it uses statistical descriptions of the probable distribution of values for each input (e.g., a mean and standard deviation for each normally distributed input value) to account for the input-associated variability that creates uncertainty in the outputs of the analysis, which helps quantify the risk in any decisions that are made on the basis of the outputs. A distribution of output values (often derived from numerical simulations involving input variables that have been randomly selected from populations of values that represent the input variable distributions) is produced to provide users with information for understanding the variability of the results and the confidence that can be placed in the analysis. Figure 10-2 provides an example illustration of the results of a probabilistic analysis.

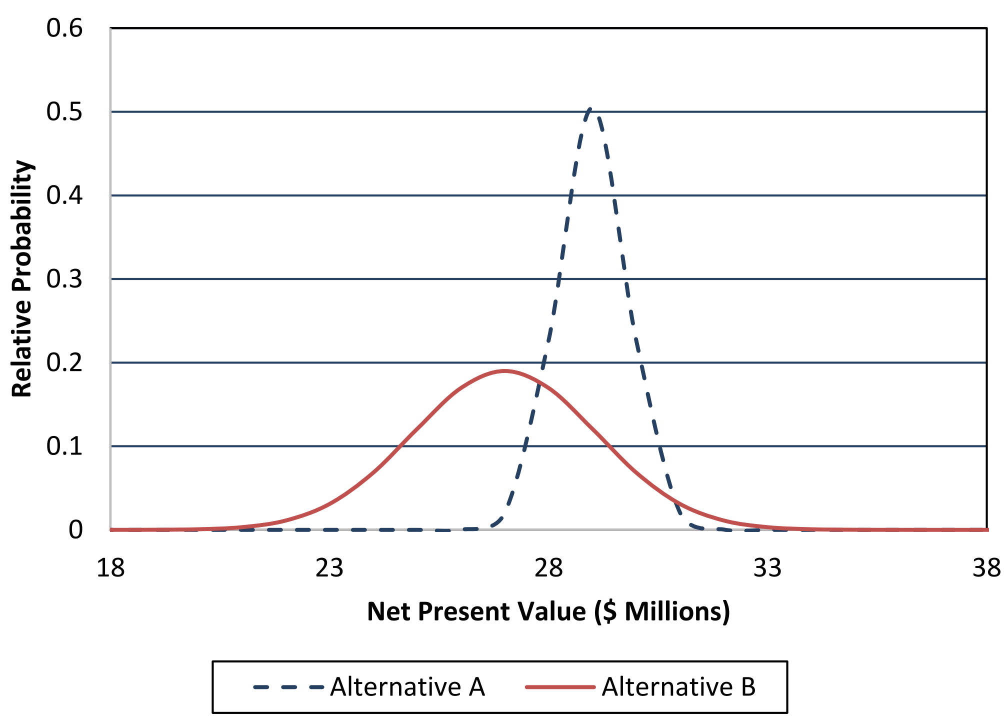



Figure 10-2. Probabilistic analysis of two design alternatives (Walls and Smith 1998).

The development of appropriate input-value distributions can be time-consuming, particularly if the data required to develop the input distributions are not routinely collected or available. The collection and use of good pavement cost, performance, and maintenance activity information is essential for the conduct of a good LCCA. The probabilistic LCCA approach typically requires the use of sophisticated computer software (such as the FHWA's *RealCost* tool), but is generally considered to have the potential for providing the most accurate "real-world" economic analysis and assessment of risk.

## Use of LCCA in Various Pavement Delivery Approaches

LCCA can be used to improve decisions made in different types of pavement delivery approaches. For example, in traditional design-bid-build (DBB) programs, LCCA (along with other criteria) is typically used by the owner/agency to aid in determining the pavement type and principal design features (e.g., full-depth HMA vs. deep-strength HMA or JPCP vs. CRCP designs) based on very preliminary project assumptions and design inputs. Knowledge of the selected pavement type and principal design is used by planners, designers, right-of-way (ROW) acquisition teams, and others to develop the detailed designs, purchase ROW, and prepare bid documents that are specific to the project and the selected pavement type.

As mentioned previously, user costs are commonly excluded from DBB project LCCA, but they may be recognized in the bidding process through "A + B" bidding. In this type of bidding, contractors submit both a bid price (A) and a number of days to complete the project construction (B), which is multiplied by some value that represents the impact on users caused by the duration of the construction activity and associated congestion and delays. Longer planned construction windows effectively increase the contractors' bid prices, making them less competitive. There are typically substantial financial penalties for exceeding the contracted number of work days, and often incentives for completing the work early.

"A + B" bidding recognizes only the impact of initial construction on user costs, and it is assumed that future agency maintenance costs and associated user costs (for work zone delays during future M&R activities) will be constant, regardless of which contractor builds the project. However, in "alternate design, alternate bid (ADAB)" projects, where the contractor can choose to bid on the construction of a specific design from among different design options, the future agency and user costs may differ significantly between the design options. In these cases, "A + B" bidding takes on a different meaning, where A is defined as the price of each contractor's bid and B is the present value of future agency maintenance and rehabilitation costs for each alternative (note: B can also be computed as a difference in future costs between alternatives that is only applied to the alternatives with the higher NPV of future costs). Given the uncertainty in estimating future activity costs and timing, alternatives with NPVs that differ by less than 10 percent are often considered to have similar costs to the agency. Since user costs are not considered directly in the analyses, the NPV of user costs for competing alternatives should be approximately equal for ADAB project alternatives. When the difference in NPV of user cost streams exceeds 20 percent, "the suitability of the project for (ADAB) should be carefully evaluated" (FHWA 2012).

The use of LCCA in design-build (DB) contracting is similar to its use in DBB contracting in that the analysis can be used to estimate future agency (and user) costs for a particular type of pavement design. The owner/agency can then use this information in evaluating the preliminary designs and construction bid packages prepared by competing engineer-contractor consortiums to determine the overall best value to the agency (considering both the initial costs and the expected future costs).

In design-build-maintain (DBM) contracting, the successful contractor is responsible for designing, constructing, and maintaining the pavement at a specified level on behalf of the owner for a predetermined period of time that generally approaches the expected pavement life. The contractor bids typically reflect both a construction cost and an annual maintenance cost over the contract. The agency can use LCCA to determine the present value of these costs and can also factor in anticipated user costs (both during initial construction and future maintenance activities) to help in identifying the best value proposal (in consideration of other nonmonetary factors as well).

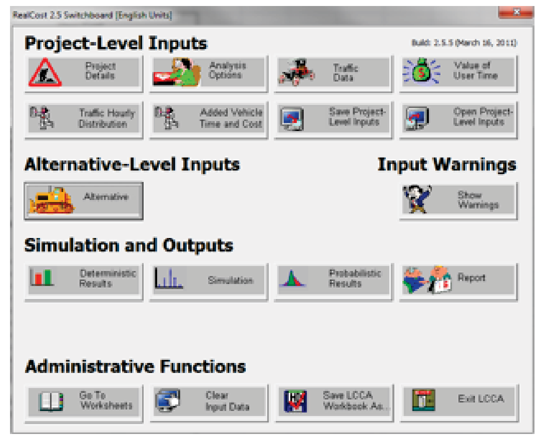
## Available LCCA Tools

Since basic LCCA can be performed simply using pencil and paper, calculator, or spreadsheet programs, it is no surprise that there are probably many such tools available. In fact, many state highway agencies have developed and adopted their own software (generally computer-based spreadsheets) that incorporate their own predetermined unit costs, discount rates, assumed maintenance cycles, and other policy-based or standard parameters to facilitate uniform LCCAs by their staff and consultants. These LCCAs are usually deterministic and provide the users with relatively little flexibility in inputs.

The most widely accepted and adopted LCCA tool for pavement applications currently in use in the U.S. is the FHWA's *RealCost* Software. Originally developed as a relatively simple proof-of-concept, spreadsheet-based program for use in LCCA workshops in 1997, it has undergone numerous improvements and enhancements over the years and is routinely used by pavement design practitioners throughout the country.

### *RealCost* LCCA Software

*RealCost is essentially an MS-Excel® spreadsheet based automated version of the LCCA methodology contained in the FHWA's LCCA Technical Bulletin (Walls and Smith 1998). The program can be used to compute life-cycle costs for agency and work zone user costs associated with new construction, maintenance, and rehabilitation activities using both deterministic and probabilistic approaches. The menu options available in the software's user interface are show in the figure below.*




*RealCost, however, does not compute agency costs or service lives for individual construction, maintenance, and rehabilitation activities. These values are typically established by the owner/agency prior to the analysis. While RealCost presents comparisons between agency and user life-cycle costs of programmed alternatives, these values alone are not sufficient in making a selection on the ideal option for a particular project. Other environmental, societal, and agency specific factors also need to be considered in arriving at the final decision. As with any other analytical tool, RealCost provides useful economic metrics that help in the overall decision-making process.*

### Examples

Numerous LCCA examples exist in agency and industry technical, reports, bulletins and training course materials (e.g., ACPA 2011; FHWA 2002; NHI 2008; West et al. 2012). For the most part, the examples included in those documents provide examples of LCCA for the purpose of pavement type selection and the selection of rehabilitation strategies.

Documentation of the use of LCCA for applications more closely related to sustainability include the following:

- Ram et al. (2011) studied a series of Michigan concrete pavement projects using both LCCA and LCA, concluding that higher levels of sustainability are achieved with increased pavement longevity.
- Embacher and Snyder (2001) used LCCA to investigate actual maintenance and rehabilitation costs and strategies for concrete and asphalt pavements in two Minnesota counties, documenting the impact of differing maintenance strategies on the normalized costs (adjusted for varying traffic levels) of comparable pavements.
- Hicks and Epps (1996) used LCCA to examine the cost effectiveness of using asphalt rubber as an alternative to traditional HMA. They concluded that, for the scenarios evaluated, asphalt rubber is a cost-effective alternative for many (but not all) highway pavement applications. When variability of the inputs was considered (e.g., cost, expected life), the asphalt rubber alternates were the best choices in most of the applications considered.

These three studies are presented as examples of the application of LCCA in making decisions that are related to pavement sustainability (beyond pure economics). The conclusions drawn from these studies are project specific and are not presented as universally applicable findings. It is important that the specific details of each analysis be considered in evaluating the conclusions drawn in these studies.

## Life-Cycle Assessment (LCA)

Awareness of the importance of environmental protection, and the possible impacts associated with the production, use, and retirement of products, has generated considerable interest in the use of assessment methods to better understand and address those impacts. Life-cycle assessment (LCA) is one of the techniques developed for this purpose. This section includes an introduction to the purpose, approach, intended outcomes, and limitations associated with the use of LCA.

### Purpose of an LCA

LCA is a structured evaluation methodology that quantifies the environmental impacts over the full life cycle of a product or system, including impacts that occur throughout the supply chain. LCA can be used for a variety of purposes, including:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle.
- Informing and guiding decision makers in industry, government, and non-governmental organizations for a number of purposes, including strategic planning, priority setting, product or process design selection, and redesign.

- Selecting relevant indicators of environmental performance from a system-wide perspective.
- Quantifying information on the environmental performance of a product or system (e.g., to implement an eco-labeling scheme, make an environmental claim, or produce an environmental product declaration statement).

Differences in results from an LCA can guide decision makers into making choices that have a lower or reduced environmental impacts.

LCA is one of several environmental assessment techniques, and may not be the most appropriate technique for use in all situations. For example, environmental impact statement (EIS) or risk assessment may be more appropriate in some cases. An EIS is a detailed analysis that serves to ensure that the policies and goals defined in NEPA, the National Environmental Policy Act, are infused into the ongoing programs and actions of the federal agency. EISs are generally prepared for projects that the proposing agency views as having significant prospective environmental impacts. The EIS should provide a discussion of significant environmental impacts and reasonable alternatives that would avoid or minimize adverse impacts or enhance the quality of the human environment, whereas an LCA is focusing more on the environmental impacts associated with the material and energy flows throughout the pavement life cycle.

## The LCA Process

LCA quantifies environmental flows that occur throughout a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (in other words, from cradle to grave). In LCA, these are referred to as life-cycle stages (or phases), and these were introduced in chapter 2 for pavement systems.

As shown in figure 10-3, there are four phases in an LCA study:

1. The goal and scope definition phase.
2. The inventory analysis phase.
3. The impact assessment phase.
4. The interpretation phase.

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

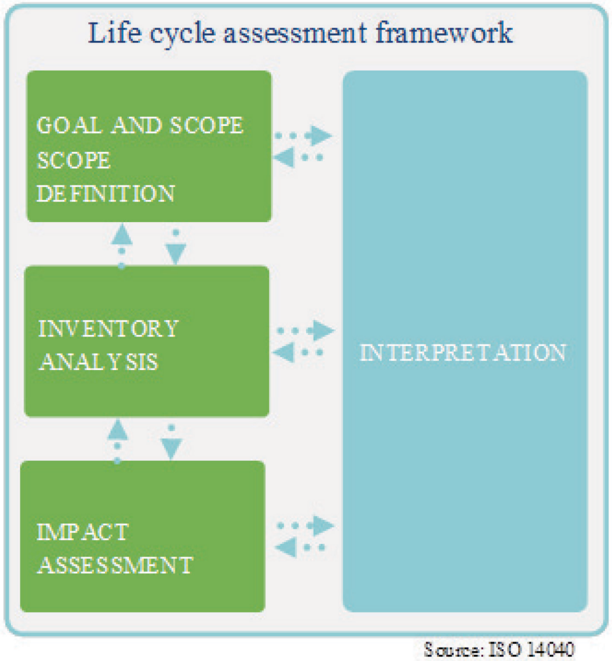



Figure 10-3. Life-cycle assessment framework (ISO 2006a).
This figure is adapted from ISO 14040:2006, Figure 1 on page 8, with the permission of ANSI on behalf of ISO. (c) ISO 2013 - All rights reserved.

The second phase of an LCA, the life-cycle inventory analysis phase (LCI phase), is the accounting stage where environmental flows (inputs of material, energy, and resources, and outputs of waste, pollution, and co-products) are tracked for the system being studied. Figure 10-4 illustrates the types of data that are collected.

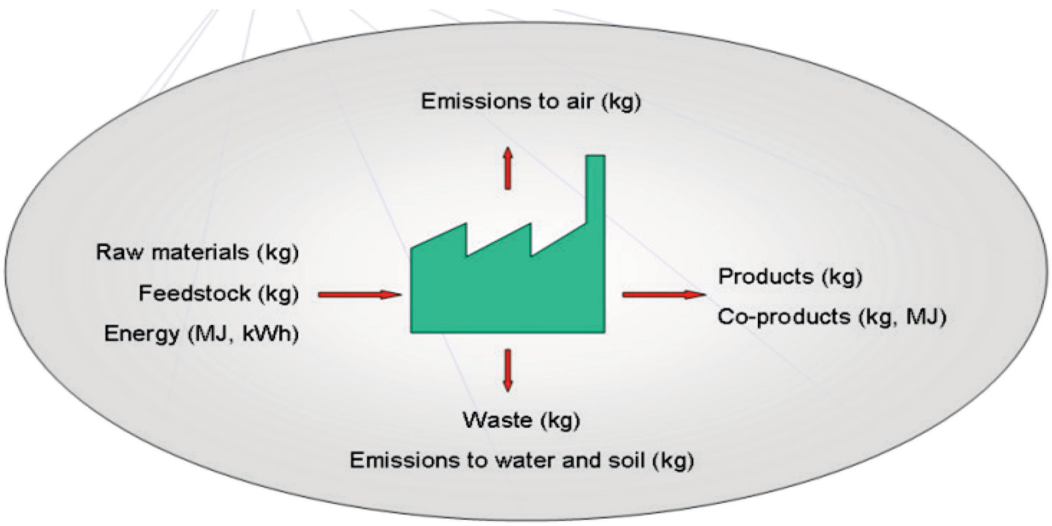



Figure 10-4. Data types relevant to a typical LCA (courtesy of theRightenvironment).

The life-cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to better understand the environmental significance of the LCI by translating environmental flows in to environmental impacts that are presented in different impact categories, typically:

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

A list of typical impact categories is included in table 10-1. LCA studies usually include a selection of impact categories that are most relevant to the specific project goal and scope, and can range from narrowly focusing on energy and energy-related emissions to a full set of impact categories. The most commonly used impact categories in the U.S. are based on the TRACI impact assessment methodology developed by the EPA, the most recent version of which (TRACI v2.0) was released in 2012 (Bare 2011; EPA 2012b). The most widely used global impact assessment method is the CML methodology (Guinée et.al. 2002), with the most recent update from April 2013.

Table 10-1. Typical LCA impact categories.

| Group | Impact Category | Geographical scale | Comment on Available Impact factors |
|---|---|---|---|
| Energy use | Fuel, non-renewable[1]<br>Resources, non-renewable<br>Resources, non-renewable, secondary<br>Fuel, renewable<br>Resource, renewable<br>Resource, renewable, secondary | Global | Small uncertainty, both energy use and feedstock energy should be quantified |
| Resource use | Resource, renewable<br>Resources, non-renewable[2] | Global | Small uncertainty |
| Emissions | Climate Change[1, 2] | Global | Small uncertainty, typical 100 year time horizon, biogenic $CO_2$ requires special attention |
| | Ozone layer depletion[1, 2] | Global | Small uncertainty |
| | Acidification[1, 2] | Regional | Small uncertainty |
| | Tropospheric ozone[1, 2] | Local | Medium uncertainty |
| | Eutrophication[1, 2] | Local | Small uncertainty, local |
| Toxicity | Human toxicity[2], respiratory[1]<br>Human toxicity, carcinogenic[1]<br>Human toxicity, non-carcinogenic[1]<br>Ecotoxicity[1], fresh water[2]<br>Ecotoxicity, marine water[2]<br>Ecotoxicity, soil[2] | All scales | High uncertainty, incomplete |
| Water | Fresh water use | Local | Small uncertainty |
| Waste | Hazardous<br>Non-hazardous | Local | Small uncertainty |

[1] part of TRACI
[2] part of CML

The life-cycle interpretation is the last phase of the LCA procedure, in which the results are summarized and discussed as a basis for conclusions, recommendations, and decision making in accordance with the goal and scope definition.

## Types of LCA Studies

There are cases where the goals of an LCA may be satisfied by performing only an inventory analysis and an interpretation. This is usually referred to as an LCI study. Generally, the information developed in an LCA or LCI study can be used as part of a much more comprehensive decision process. Comparing the results of different LCA or LCI studies is only possible if the assumptions and context of each study are equivalent. To address this, the ISO 14044 standard contains several requirements and recommendations to ensure transparency on these issues (ISO 2006b).

## Most Pavement LCAs are Process Based and "Attributional"

Most pavement-oriented LCA studies are process based, meaning that data are collected for every process that is covered in the LCA. This is a bottom-up approach, and while data intensive it does allow for specific, regionalized, and representative results. Several commercial database and software tools are available that are based on this type of LCA.

Other LCA studies are based on data generated from a top-down approach, called input-output LCA. These LCAs produce estimates of total supply chain impacts for economic sectors using economic input-output tables (which trace dollar flows across sectors) linked with resource use information and pollution flows for economic sectors. Products within a sector are assigned a portion of a sector's supply chain impact based on their value. LCAs sometimes follow a hybrid approach where input-output data are used for secondary data and process LCI data are used for the primary processes, materials, and life-cycle phases that are under consideration.

Regardless of whether the LCA is process based or input-output, pavement-oriented LCA studies most often are attributional, meaning they focus on describing the overall environmental properties of a life cycle and its subsystems. This is very useful in understanding the overall impact of a pavement project, for example. On the other hand, some pavement LCA studies that have been conducted are consequential, meaning that they aim to describe the environmental impacts of changes to an evaluated system. This can be useful in evaluating system wide impacts and is often used for studies that evaluate the impact of a proposed change in policy. Additionally, consequential LCA can be useful for infrastructure and traffic planning studies that evaluate decisions that have longer term and more far-reaching consequences.

## Available Tools

Although there are no generally accepted LCA tools for pavements in the U.S., there are a number of LCA software programs (e.g., Athena, Gabi, SimaPro) that include relevant LCI datasets (many of which are proprietary) that can be used to develop LCA models. There are some pavement modeling tools available as well, such as PaLATE, which uses a hybrid LCA approach and considers energy use, air emissions, and leachate; information on this tool can be found at http://www.ce.berkeley.edu/~horvath/palate.html, but the tool is no longer maintained. This renders the database outdated and not fit-for-purpose. An update of the database would be required to make this a useful tool. This could leverage the results from LCI databases that rely less on input-output based LCI models.

More recently, the Project Emissions Estimator (PE-2) tool has been developed and provides a GHG emissions model for construction, maintenance, and use of pavements[1] (Mukherjee, Stawowy, and Cass 2013). Additionally, AASHTO has also released a tool, GreenDOT, that estimates carbon dioxide emissions from the operations, construction, and maintenance activities of state highway agencies; it is designed to calculate emissions for geographical areas ranging from a single project to an entire state, and over time periods ranging from 1 day to several years (Gallivan, Ang-Olson, and Papson 2010). The two most likely uses of the GreenDOT tool are to calculate annual agency-wide emissions or to calculate emissions related to a specific project, covering a period of days or years[2].

Most of these models rely on publicly available $CO_2$ emissions factors such as those derived from MOVES, NONROAD and GREET. The EPA's MOVES (Motor Vehicle Emission Simulator) (EPA 2012a) and NONROAD (EPA 2005) are air emissions inventory models and thus can be used to estimate on-road or non-road mobile source emissions (i.e., tailpipe emissions) associated with vehicles and equipment, but not life-cycle emissions. The GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model) model, developed by the Argonne National Laboratory, includes life-cycle emission and energy factors for different fuels, electricity, and other energy sources (ANL 2013).

The Canadian Athena Institute released the most comprehensive North American LCA tool, a Highway Impact Estimator that relies on generic LCI data that the user cannot alter (Athena 2013). There are many other examples of pavement LCA tools from Europe, including the decision-weighting model for roads, where the material life cycle of pavement can be modeled for environmental, economical, and user-defined project-specific sustainability aspects (Van Leest, Van Hartskamp, and Meijer 2008), and the RWS model DuboCalc[3], which is an LCA model for the Dutch DOT that is mandated for use in all highway infrastructure. Other entities have developed their own models, often tailored for specific research projects or regional decision making including models developed at universities or by regional authorities.

## Key Issues

Pavement LCA methods and models continue to evolve. To illustrate some of the challenges that lie ahead, a short summary of the key issues that must be addressed to advance the use and implementation of LCA for pavements is provided below:

- A general pavement LCA framework has not yet been agreed upon by practitioners. When pavement LCA studies are executed, LCA practitioners have to make many assumptions and make methodological choices that can lead to confusing and contradictory results among studies. The development of a generic pavement LCA framework could create a template that would define the most relevant starting points (i.e., for scope, goal, system boundaries, etc.) for any pavement LCA going forward. This would not only make LCAs easier to perform, but would also make them easier to interpret and compare.
- There is a need for a centralized database of non-proprietary LCIs for materials, equipment, vehicles, and other elements that can serve as a reference database for

[1] http://www.construction.mtu.edu/cass_reports/webpage/plca_estimator.php

[2] http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25(58)_GreenDOTv1-5b.xls

[3] http://www.rijkswaterstaat.nl/zakelijk/duurzaam/duurzaam_inkopen/duurzaamheid_bij_contracten_en_aanbestedingen/dubocalc/index.aspx

pavement LCA. This database would be used in conjunction with primary project data, and would include generic data covering all upstream data or "cradle-to-gate" data. A significant amount of data needs to be developed, preferably in a harmonized framework, such as an EPD framework for materials.

- A pavement life cycle can extend over a period of 60 to 75 years, and modeling a complete life cycle means making a number of assumptions based on design parameters, anticipated performance, maintenance and rehabilitation timing and frequency, and so on. It is extremely difficult to predict all these parameters today for the years to come. Transparently reporting the uncertainty in these assumptions is one step to improving LCAs.
- When the use phase is included, traffic-related impacts often dominate other life-cycle stages. Some key traffic-related elements are traffic composition, volume, traffic delays, future traffic, vehicle fuel efficiency, rolling resistance, and pavement smoothness. The LCA models for these elements are still in development, and some still require basic research, especially with regards to vehicle and pavement interactions including the effect of pavement condition on vehicle fuel efficiency.

## Example Studies

A number of relevant pavement LCA studies have been performed in the last few years, with some of the significant findings and conclusions from selected studies summarized below.

- Generally, most pavement LCA studies find that the materials for construction and overlays dominate the results when vehicle traffic is excluded from the analysis. This is true for both asphalt and concrete pavements. The combination of manufacturing the binder and producing the resultant mixture is a relevant contributor to the results for both pavement types. Aggregates constitute the majority of the mass of the pavement, making transportation and logistics particularly relevant for recycling and virgin aggregates.
- The energy used and the emissions generated from the traffic that uses the pavement facility typically outweigh the emissions produced during the production of the materials and construction of the pavement. Steps towards cleaner fuels, higher fuel efficiency of the vehicles, and better traffic flow are relevant and potentially significant. This last point also favors nighttime work when traffic disruptions are minimized (Santero, Masanet, and Horvath 2010).
- Ram et.al. (2011) studied a series of concrete pavement projects in Michigan using LCCA and LCA tools, and concluded that increased pavement longevity was associated with reduced environmental impacts. Additionally, it was noted that if longevity is achieved, the use of SCM and RCA results in further improvements in both the economic and environmental life-cycle indicators.
- Wang et.al. (2012) applied LCA of pavement to research the impact of pavement smoothness over time and the relation between pavement maintenance and preservation on the fuel efficiency of vehicles for California state highways. The study found that the application of preservation treatments that enhance smoothness has a net positive effect on the overall energy and GHG emissions for facilities carrying high traffic volumes.
- The time period that is covered by the LCA model is a very important factor. Typically, pavements are modeled using existing design criteria, construction practices and planned maintenance, rehabilitation, and replacement cycles, even though it is acknowledged that

these practices are constantly changing. Studies tend to use estimates for typical practices and use considerations such as traffic volume, traffic delays, and fuel efficiency over this long period of time, but these estimates become more and more uncertain as they are projected further into the future (Santero, Masanet and Horvath 2010).

### Methodological Framework in Greater Detail

The general framework for LCA is defined in the ISO 14040 series, with the most prominent one the ISO 14044 standard that defines the general requirements and guidelines (ISO 2006a). The standard provides a framework that encourages transparency and some consistency in approaches and reporting. However, because the ISO standard applies to LCAs for all products and systems, it does not prescribe an approach tailored to specific categories of analysis, such as for an LCA of pavements. Still, even though there is no generally accepted LCA framework for pavements, there are some important developments that should be noted. For example, a basic framework for pavement LCA was developed in 2010 that builds on the ISO guidelines and provides pavement-specific methodological guidelines (UCPRC 2010).

The European industry is organized in a technical working group that is defining pavement specific guidelines under the Construction Products Directive. It details the LCA process for products, buildings, and construction works. The CEN 15804 lays down a structure for product LCA and Environmental Product Declarations (CEN 2012). The focus of the CEN/TC 350/WG 6 is to develop a framework for Civil Engineering Works, and it is estimated that a standard will be developed by 2016.

ISO 14044 includes an important section that is meant to ensure that LCAs are methodologically sound and adhere to accepted practices. In section 6, rules and requirements are laid down for critical review, especially when comparisons are made with the aim of external publication. Depending on the goal and scope of the LCA, a critical review by an independent LCA expert is sufficient. For competitive LCAs, a critical review panel (consisting of at least three members, one of which needs to be an LCA expert and two that need to be independent industry experts) needs to be instituted.

Although reviews are currently not common practice in pavement LCA, except when published as peer-reviewed articles, some recent studies have incorporated a review component. It is recommended that future work incorporate a critical review process and greater stakeholder involvement, which should lead to increased standardization and enhanced LCA practices.

### What Lies Ahead: Environmental Product Declarations

An EPD, as defined in the ISO 14025 standard (ISO 2006c), is a declared LCA for a product and is a form of certification. If all products had an EPD, a pavement LCA using those products would benefit tremendously in terms of quality and lower cost. EPDs can be issued on a specific product from a specific producer, but may also be issued for a generic product from a group of manufacturers (such as an association). Figure 10-5 shows a sample EPD for a concrete mix design.

Summary of
**Environmental Product Declaration**

**Central Concrete**

Mix 340PG9Q1

San Jose Service Area

EF V2 Gen Use P4000 3" Line 50% SCM

**Performance Metrics**

| | |
|---|---|
| 28-day compressive strength | 4,000 psi |
| Slump | 4.0 in |

**Environmental Impacts**

| Impact name | Unit | Impact per m3 | Impact per cyd |
|---|---|---|---|
| Total primary energy consumption | MJ | 2,491 | 1,906 |
| Concrete water use (batch) | m3 | 6.66E-2 | 5.10E-2 |
| Concrete water use (wash) | m3 | 8.56E-3 | 6.55E-3 |
| Global warming potential | kg CO2-eq | 271 | 207 |
| Ozone depletion | kg CFC-11-eq | 5.40E-6 | 4.14E-6 |
| Acidification | kg SO2-eq | 2.26 | 1.73 |
| Eutrophication | kg N-eq | 1.31E-1 | 1.00E-1 |
| Photochemical ozone creation | kg O3-eq | 46.6 | 35.7 |

A sample EPD for a concrete mix design by Central Concrete Supply Co.

*Credit: Central Concrete Supply*

Figure 10-5. Sample EPD for a concrete mix design (courtesy of Central Concrete Supply Company).

The basis for an EPD is a Product Category Rule (PCR) document generated through a stakeholder procedure and including rules for specific product categories. Two recent examples of industry involvement in this area are: 1) the Product Category Rules Task Group produced a draft PCR for portland and blended cements in 2012 and is close to releasing a publication, and, 2) the National Ready Mixed Concrete Association (NRMCA) is certifying EPDs for cement (Carbon Leadership Forum 2010) and concrete (Carbon Leadership Forum 2013) as a program operator. In addition, the National Asphalt Pavement Association (NAPA) has formed a task group to develop PCRs and EPDs for the asphalt pavement industry.

**Product Category Rules**

- *The Product Category Rule (PCR) document defines the rules for a product LCA, is industry accepted, and defines the Environmental Product Declaration (EPD) format. It is owned by a Program Operator.*
- *The LCA can be drafted against the PCR document.*
- *The EPD follows the PCR requirements and uses the results from the LCA.*
- *An independent third party performs a verification of the LCA and EPD against the PCR after which the Program Operator issues the EPD.*

## An Example of an Important Methodological Element: Allocation

There are several important methodological elements to an LCA, but one that is keeping the LCA community engaged is the aspect of allocation. This topic is not limited to just pavement LCA, but is relevant to all LCA studies. This section is included to highlight some of the ongoing discussions that are relevant to pavement LCA. All elements of the pavement life cycle are germane to allocation, but this discussion on allocation is focused on material sources that are discussed in chapter 3 and on material recycling performed at the end of the life of the pavement that are discussed in chapter 8. Those chapters include several callout boxes that relate to allocation, and this section aims to tie it together.

Whenever a system of production yields multiple products or services, the environmental inputs and outputs of the system have to be assigned to each product and service, referred to as co-products. The ISO 14040 standards for LCA prescribe a hierarchical preference for how to assign, or *allocate*, environmental flows that occur in the modeling of the LCA. These allocations must be assigned whenever a production system boundary is crossed. For example, when one pavement life cycle ends and another begins, allocation must be utilized when assigning environmental impact to the material that is recycled from the pavement.

A general consensus among LCA practitioners and those involved in evaluating products and systems is that allocation rules should be set up to:

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

In addition, ISO standards, such as ISO 14044 for LCA, require sensitivity analysis to evaluate the impact of allocation rules to determine how they might change the final results of the assessment. According to ISO standards, the preference for treating co-products is to first try to avoid allocation by either 1) subdividing the production system into processes that can be assigned wholly to a single co-product, or 2) expanding the scope of interest to include the processes that seem to need allocation, thereby removing the need for allocation (this is referred to as system expansion). System expansion is more or less equivalent to displacement or substitution, where co-products are modeled as if they are displacing equivalent products in the marketplace. Thus, the system of production is credited with avoiding the need for producing these equivalent products. This approach is often used in consequential LCA approaches, as described earlier.

In most pavement LCA studies, the boundaries for the system of production are crossed (and thus allocation is necessary) in three situations:

1. Multi-output situations like manufacturing processes with co-products (e.g., oil refineries).
2. Reuse of components and recycling of materials after initial use, such as steel rebar, reclaimed asphalt pavement, coal combustion co-products from power generation, or use of discarded tires in asphalt binder.
3. Multi-input situations like waste treatment processes, such as incineration and landfilling.

All three situations are described below with examples of some actual processes and materials in pavement LCA.

### *Manufacturing Processes with Co-Products*

The preferred way to deal with assigning impacts to multi-outputs is to reflect the physical properties of the outgoing flows, such as mass or energy content. If a relationship can be established that is more suitable than mass, it should be used. This means that the physical basis for allocation can be different in different situations and for different materials. The economic value of co-products can also be used for allocation; however, Bernard, Blomberg, and Southern

(2012) suggest that allocation based on physicochemical properties (e.g., mass or energy content) is preferred to economic allocation. With that being said, Ayer et al. (2007), Basset-Mens and van der Werf (2005), and Guinee et al. (2002), among others, have stated a preference for economic allocation above other approaches, largely because economic value is typically the primary driver of business.

Allocation requires a somewhat arbitrary partitioning of the co-producing processes without considering the interactions between subprocesses; thus, an objective justification is warranted between the chosen allocation parameter, such as mass or economic value, and the share of environmental loads (Weidema 2001). This makes co-product allocation sometimes contentious. Good LCA practice in this case requires justification of the grounds for allocation, transparency in reporting, showing the impact of allocation choices on the results, and performing sensitivity analyses to assess the significance of the allocation choice on the overall LCA conclusions. Some examples are provided in chapter 3 for specific materials (e.g., asphalt as a co-product from the petroleum refinery). An example of an economic allocation for a multi-output process is show in figure 10-6.

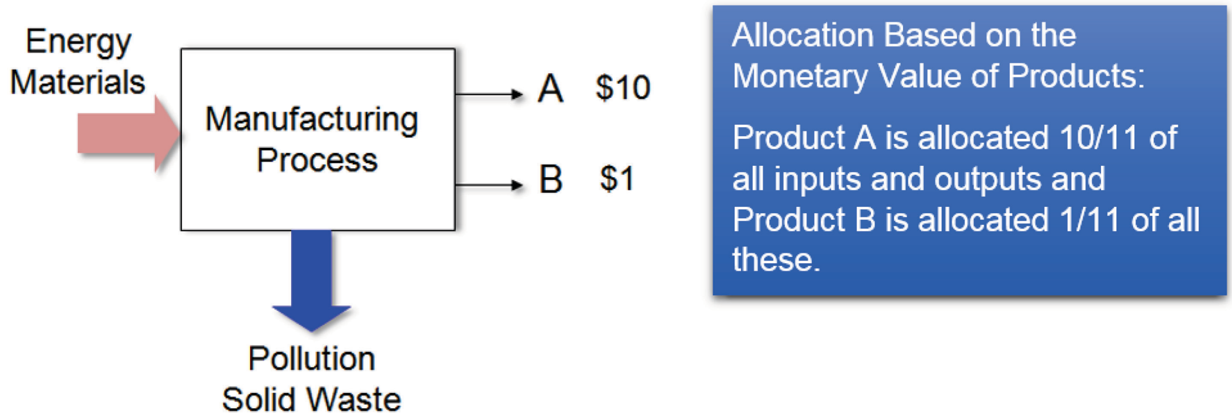



Figure 10-6. Example of economic allocation for a multi-output process.

### *Reuse of Components and Recycling of Materials after Initial Use*

When using a material from another product, pavement or system, several approaches for allocation have been and are being tried to ensure that the "benefits" of using secondary materials or fuel resources are properly reflected in an LCA.

Most EPD approaches use a strict and conservative approach: all processes and transportation needed to reuse or recycle the material are assigned to the product utilizing the recycled content, but the production of the original product is assigned to the first product's life cycle. The same is true of reused or recycled materials that are used in pavement projects, such as the secondary content in steel, recycled aggregate from building waste, rubberized asphalt binder containing recycled tires, recovered binder from asphalt shingles, and SCMs derived from other industrial processes. Furthermore, materials that become available for reuse or recycling at the end of the pavement life cycle, such as RAP, RCA, and reinforcing steel, are also allocated in this manner.

An important element in this discussion is whether a material is defined as a waste or a product. If an economic approach is used to define a resource as a waste or a co-product, the following reasoning can be used:

- Where a waste flow material has value, it is considered a co-product and needs to have "production" processes allocated to it for the life cycle that is using the material. In essence, as soon as a waste flow has positive economic value, it is considered a co-product and should be treated as such.
- Where a waste flow material has a negative cost but becomes an economically valuable product through processing, the impact of processing and handling is allocated based on the difference between the cost (assigned to the producing life cycle where the waste occurred) and the positive value (assigned to the receiving life cycle where the co-product is used). An example of this is concrete waste that requires an acceptance fee at a crushing facility where it is processed (crushed and sized), and then sold back to the market at a price.
- Where the waste remains a cost regardless of processing, all environmental burdens of the processes are assigned to the producing life cycle; in this case, it essentially stays a waste and never becomes a co-product. The life cycle that uses materials like this are essentially part of the waste treatment process and receive the material "for free."

Other approaches assign a "value" to the recycled materials and include credits for preventing the need for new primary materials for the new application. This is referred to as substitution, and must be considered cautiously and aligned with the approach for the receiving product system. Double counting of credits should be prevented.

One variation of assigning credits for recycling is the modeling of multiple life cycles to reflect repeated recycling benefits. This approach is typically used to assign future recycling credits to the current product. There are examples reported where an infinite number of life cycles are modeled to show the benefits of recycling, which can extend time periods that are irrelevant on a human scale. This is not considered good LCA practice, particularly given that modeling a pavement over a period in the range of 50 to 75 years is methodologically challenging enough as it is.

### *Waste Treatment Processes*

The preferred way to deal with assigning impacts to multi-input processes is to reflect the physical properties of the incoming flows. If a relationship can be established that is more suitable than mass, it should be used. An example is the relation between the chemical composition of a waste that is available for landfill and the associated emissions to air and water from the landfill. However, this is not very relevant for most pavement LCA materials since most of them are inert. Another example is the relation between the chemical composition of a waste that is available for incineration and the associated emissions to air and energy recovery as heat or electricity. Both situations occur in pavement LCA but are not very relevant to the outcome of most pavement LCA materials since most of them are inert or have little or no economic value as a combustion energy source.

### *Final Thoughts*

Allocation is clearly a complex and contentious issue, and of particular importance to those conducting pavement LCAs given their wide range of processes and the significant amount of recycling that occurs. While it is expected that allocation will remain an ongoing topic of debate, it is recommended that the key goals for allocation should be to incentivize practices that reduce environmental impact, prevent double counting and omission of key inputs/outputs, provide fairness between industries, and be transparent about the procedure utilized.

## Sustainability Rating Systems

Transportation and associated industries offer a range of guidance on the sustainability of transportation infrastructure. This guidance ranges from generally advocated strategic directions, to more comprehensive guide documents, to rating systems that call out specific practices. Each level of guidance has value; the choice on which to use depends upon the goals and requirements of the governing agency or organization.

### Background

A sustainability rating system is essentially a list of sustainability best practices with an associated common metric. This metric, usually points, quantifies each best practice in a common unit. In this way the diverse measurement units of sustainability best practices (e.g., pollutant loading in stormwater runoff, pavement design life, tons of recycled materials, energy consumed/saved, pedestrian accessibility, ecosystem connectivity, and even the value of art) can all be compared. In its simplest form, a rating system can count every best practice equally (e.g., all worth one point), in which case the rating system amounts to a tally of the number of best practices used. In more complex forms, rating systems weight best practices (usually in relation to their impact on sustainability or priority), which can assist in choosing the most impactful best practices to use given a limited scope or budget.

Currently there are a number of national and international rating system efforts within the transportation community. These systems vary in scope and complexity but are generally designed to provide guidance, scoring, and potential rewards for the use of sustainability best practices. Rating systems usually concentrate on practices that are compatible with current regulations but are above and beyond existing minimum regulatory requirements. Rating systems are particularly appealing because they:

- Provide a common metric (points) for the entire range of sustainable solutions.
- Measure sustainability and thus make it manageable.
- Allow for straightforward communication of sustainability goals, efforts, and achievement.
- Provide a reasonable context within which designers, contractors, and material suppliers can be innovative in their solutions.

While there has been and continues to be much debate over the scientific merit and basis for rating systems, such debate can miss the point. The essential purpose of most sustainability rating systems is not a scientifically defensible taxonomy of sustainability, but rather a tool to (1) encourage sustainability practices beyond the regulatory minimum, and (2) to communicate sustainability in a comprehensible manner. In particular, rating systems provide an understandable way to communicate sustainability whether it is within an agency or project, to design and construction professionals, or to the general public. Furthermore, rating systems are often turned to when other means of quantification (e.g., LCA) fail to capture the full range of sustainability best practice impacts. For instance, while LCA is capable of accounting for GHG emissions associated with pavement construction, it is not able to capture more abstract, yet important, sustainability features such as ecological connectivity and aesthetics.

Rating systems are often criticized because (1) they tend to sacrifice detail for simplicity, (2) it is difficult to generate consensus on which items to include/exclude, (3) they do not capture the entire scope of sustainable solutions, and (4) their use in blindly pursuing points as part of a rating system could trump good design/construction. However, a well-designed rating system used within a proper organizational approach to sustainability can overcome these issues and provide value to the agency or organization.

### Rating Systems in Context

It is important to view a rating system in the right context. For instance, project-based rating systems address sustainability within the context of an individual project. Therefore, they should be considered specialized tools that fit within a broader agency approach to sustainability but do not address all agency sustainability efforts. In this context, the adoption or use of a rating system does not supply sustainability but rather complements other agency-wide efforts.

### Potential Industry Impacts of Rating Systems

Beyond a single agency, well-designed and marketed rating systems can have broad-reaching sustainability impacts within an industry. For instance, the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED®) rating system addressing building sustainability (often termed "green buildings") has been in use since 1998 and is by far the most popular sustainability rating system worldwide. It can be argued that LEED has allowed sustainable infrastructure to gain a commercial foothold in the building industry because of its success. For instance, as of April 2013 there were 16,611 LEED certified projects, 39,712 LEED registered projects, and the annual USGBC conference, GreenBuild®, attracts over 30,000 attendees and 1,000 exhibitors (USGBC 2013). Growth of the green building industry is evidenced by *Engineering News-Record's* (*ENR's*) annual survey of green contractors, most of which are working on projects pursuing LEED certification. In September 2013, *ENR*' s identified "Top 100 Green Contractors" in the U.S. received $42.75 billion in contracting revenue from green projects in 2012, which represented 34.4 percent of their total revenue (Tulacz 2013). They also identified 13,019 accredited staff in those 100 companies. While one might still argue the details of LEED rating systems, the number of certifications, registrations, and conference attendees makes a strong case for the overwhelming success of the communication aspect of the USGBC's suite of rating systems.

## Rating Systems Relevant to Pavements

While there are many rating system efforts that apply in some way to pavements worldwide, the following sections briefly outline those systems that are (1) the most prevalent on the national stage in the U.S., and (2) most relevant to pavements. Note that although all of these rating systems are relevant to pavements in some way, none of them are focused on pavements as the primary system under consideration. All focus on larger systems (e.g., road project, agency sustainability efforts, neighborhood design, infrastructure systems) and account for pavement as a contributing subsystem. Therefore, none of them should be used to rate or grade pavement sustainability in isolation because pavement tends to exist as a subsystem that contributes to larger systems (e.g., neighborhood, highway corridor, downtown street network, community, ecology).

The following sections provide overviews of several sustainability rating systems that are reasonably well developed and are being used at the national level (either actively rating projects or engaged in a pilot phase).

## INVEST (Infrastructure Voluntary Evaluation Sustainability Tool)

INVEST (FHWA 2011; Bevan et al. 2012) is a sustainability rating system for roadways that encompasses planning and policy, project development, and operations and maintenance. It is point based and voluntary and applicable to all U.S. road projects with a focus on state Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs). A summary of its characteristics is provided below.

- **Owner**: FHWA.
- **Scope**: Transportation system and project planning, design, construction, operations and maintenance.
- **Status**: (as of April 2013): Version 1.0 is available at www.sustainablehighways.org.
- **Background**: INVEST was created by the FHWA as a self-evaluation tool. There are no plans to make it required in any context. INVEST has three different subsystems that can be used independently: Systems Planning, Project Development, and Operations and Maintenance. INVEST is intended to function as a self-certification program (i.e., the project owner can also perform the review).
- **Relevance to pavements**: Systems Planning: no criteria are directly relevant to pavement sustainability concepts discussed in this document. Project Development: 14 criteria (48 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document. Operations and Maintenance: 5 criteria (36 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document.

## Greenroads®

Greenroads (Muench et al. 2011) is a sustainability rating system for roadway design and construction. It is point based and voluntary and applicable to all U.S. road projects. Relevant characteristics are given below.

- **Owner**: Greenroads Foundation (501 c3 non-profit organization).
- **Scope**: Roadway design and construction. Does not directly address planning or operations and maintenance, although a number of credits influence those items.
- **Status**: (as of April 2013): Version 1.5 is available to review projects at http://www.greenroads.org/. Six projects certified and 23 projects registered representing about $2.8 billion of construction value.
- **Background**: Greenroads was originally created by the University of Washington and CH2M HILL in partnership, now independently owned and operated by the Greenroads Foundation, and also includes an individual accreditation program. Greenroads is a third-party certification program (i.e., the Greenroads Foundation functions as an independent third party review).
- **Relevance to pavements**: 7 of 11 Project Requirements (64 percent) and 19 Voluntary Credits (49 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document.

### Envision™

Envision (ISI and Zofnass 2012) is a sustainability rating system for civil infrastructure. It is point based, voluntary, and applicable to all civil infrastructure. Important characteristics are listed below.

- **Owner**: A joint collaboration between the Zofnass Program for Sustainable Infrastructure at the Harvard University Graduate School of Design and the Institute for Sustainable Infrastructure (ISI), a joint venture of the ASCE, American Council of Engineering Companies (ACEC), and the American Public Works Association (APWA).
- **Scope**: All civil infrastructure (including roads).
- **Status**: (as of February 2014): Version 2.0 manual is available to review projects at http://www.sustainableinfrastructure.org/.
- **Background**: Envision™ has some features in common with CEEQUAL (a U.K.-based system). Also includes individual training and accreditation.
- **Relevance to pavements**: 17 credits (31 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document.

### GreenLITES

GreenLITES (Leadership In Transportation and Environmental Sustainability) is a rating program for transportation infrastructure (NYSDOT 2010). It has the following key characteristics:

- **Owner**: NYSDOT.
- **Scope**: NYSDOT project design and operations. There are two manuals, one for Project Design certification and one for Operations certification.
- **Status**: (as of April 2013): Version 2.1.0 (April 2010) for the Project Design Certification Program, and a draft version for the Operations Certification Program are available.
- **Background**: The Project Design Certification Program is used as a design review for NYSDOT projects (NYSDOT 2012). The Operations Certification Program began piloting in 2009. Both are self-certification programs meaning the NSYDOT does the project work and the certification review.
- **Relevance to pavements**: 16 credits (10 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document.

### Leadership in Energy and Environmental Design (LEED®)

LEED is a series of rating systems (nine currently) focused on buildings. Characteristics of the system are provided below.

- **Owner**: USGBC (501 c3 non-profit organization).
- **Scope**: Buildings, neighborhoods (there are nine separate rating systems).
- **Status**: (as of April 2013): Fully deployed as LEED 2009 (this equates to Version 3) at http://www.usgbc.org/. Over 16,000 projects certified worldwide and 40,000 projects registered (USGBC 2013). The next full version, LEED v4, was launched in 2013.

- **Background**: LEED has been in existence since 1998. Claims over 12,000 member organizations, more than 160,000 accredited professionals and 491 government organizations with LEED legislation, executive orders, resolutions, ordinances, policies and incentives (USGBC 2012).
- **Relevance to pavements**: For LEED ND (LEED for Neighborhood Development) (USGBC 2012), 4 credits (6 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document. All 9 LEED rating systems are focused on buildings; only a small portion of each LEED rating system is relevant to pavements. Typically, this relevance is limited to credit for recycled content, high albedo surfaces, and porous pavement.

Tables 10-2 through 10-6 show more detail about how INVEST version 1.0, Greenroads version 1.5, GreenLITES Project Design version 2.1.0, Envision version 2.0, and LEED ND 2009, respectively, address and relate to the pavement sustainability concepts described in this reference document.

Table 10-2. Summary of INVEST sustainability criteria and scoring (FHWA 2011).

| Criterion | SYSTEM PLANNING CRITERIA Title | Points Possible | Pavement Related |
|---|---|---|---|
| SP-1 | Integrated Planning: Economic Development and Land Use | 15 | |
| SP-2 | Integrated Planning: Natural Environment | 15 | |
| SP-3 | Integrated Planning: Social | 15 | |
| SP-4 | Integrated Planning: Bonus | 10 | |
| SP-5 | Access and Affordability | 15 | |
| SP-6 | Safety Planning | 15 | |
| SP-7 | Multimodal Transportation and Public Health | 15 | |
| SP-8 | Freight and Goods Movement | 15 | |
| SP-9 | Travel Demand Management | 15 | |
| SP-10 | Air Quality | 15 | |
| SP-11 | Energy and Fuels | 15 | |
| SP-12 | Financial Sustainability | 15 | |
| SP-13 | Analysis Methods | 15 | |
| SP-14 | Transportation Systems Management and Operations | 15 | |
| SP-15 | Linking Asset Management and Planning | 15 | |
| SP-16 | Infrastructure Resiliency | 15 | |
| SP-17 | Linking Planning and NEPA | 15 | |
| | **Total Points** | **250** | **0** |
| | **Percentage of points directly relevant to pavement** | | **0%** |

Table 10-2. Summary of INVEST sustainability criteria and scoring (FHWA 2011) (continued).

| **Criterion** | **PROJECT DEVELOPMENT CRITERIA Title** | **Points Possible** | **Pavement Related** |
|---|---|---|---|
| PD-1 | Economic Analysis | 5 | |
| PD-2 | Lifecycle Cost Analysis | 3 | ✓ |
| PD-3 | Context Sensitive Project Development | 5 | |
| PD-4 | Highway and Traffic Safety | 10 | ✓ |
| PD-5 | Educational Outreach | 2 | |
| PD-6 | Tracking Environmental Commitments | 5 | ✓ |
| PD-7 | Habitat Restoration | 3 | |
| PD-8 | Stormwater | 9 | |
| PD-9 | Ecological Connectivity | 3 | |
| PD-10 | Pedestrian Access | 2 | |
| PD-11 | Bicycle Access | 2 | |
| PD-12 | Transit and HOV Access | 5 | |
| PD-13 | Freight Mobility | 7 | |
| PD-14 | ITS for System Operations | 5 | |
| PD-15 | Historical, Archaeological, and Cultural Preservation | 3 | |
| PD-16 | Scenic, Natural, or Recreational Qualities | 3 | |
| PD-17 | Energy Efficiency | 8 | |
| PD-18 | Site Vegetation | 3 | |
| PD-19 | Reduce and Reuse Materials | 8 | ✓ |
| PD-20 | Recycle Materials | 8 | ✓ |
| PD-21 | Earthwork Balance | 3 | |
| PD-22 | Long-Life Pavement Design | 5 | ✓ |
| PD-23 | Reduced Energy and Emissions in Pavement Materials | 3 | ✓ |
| PD-24 | Contractor Warranty | 3 | ✓ |
| PD-25 | Construction Environmental Training | 1 | ✓ |
| PD-26 | Construction Equipment Emission Reduction | 2 | ✓ |
| PD-27 | Construction Noise Mitigation | 2 | ✓ |
| PD-28 | Construction Quality Assurance Plan | 5 | ✓ |
| PD-29 | Construction Waste Management | 3 | ✓ |
| | **Total Points** | **126** | **58** |
| | **Percentage of points directly relevant to pavement** | | **46%** |
| | | | |
| **Criterion** | OPERATIONS AND MAINTENANCE CRITERIA Title | Points Possible | Pavement Related |
| OM-1 | Internal Sustainability Plan | 15 | |
| OM-2 | Electrical Energy Efficiency and Use | 15 | |
| OM-3 | Vehicle Fuel Efficiency and Use | 15 | |
| OM-4 | Reuse and Recycle | 15 | ✓ |
| OM-5 | Safety Management | 15 | |
| OM-6 | Environmental Commitments Tracking System | 15 | |
| OM-7 | Pavement Management System | 15 | ✓ |
| OM-8 | Bridge Management System | 15 | |
| OM-9 | Maintenance Management System | 15 | ✓ |
| OM-10 | Highway Infrastructure Preservation and Maintenance | 15 | ✓ |
| OM-11 | Traffic Control Infrastructure Maintenance | 15 | |
| OM-12 | Road Weather Management Program | 15 | |
| OM-13 | Transportation Management and Operations | 15 | |
| OM-14 | Work Zone Traffic Control | 15 | ✓ |
| | **Total Points** | **210** | **75** |
| | **Percentage of points directly relevant to pavement** | | **36%** |

Table 10-3. Summary of Greenroads credit categories and scoring (Muench et al. 2011).

| Credit | Title | Points Possible | Pavement Related |
|---|---|---|---|
| | ***Project Requirements*** | | |
| PR-1 | Environmental Review Process | NA | |
| PR-2 | Lifecycle Cost Analysis | NA | ✓ |
| PR-3 | Lifecycle Inventory | NA | ✓ |
| PR-4 | Quality Assurance Plan | NA | ✓ |
| PR-5 | Noise Mitigation Plan | NA | ✓ |
| PR-6 | Waste Management Plan | NA | ✓ |
| PR-7 | Pollution Prevention Plan | NA | |
| PR-8 | Low-Impact Development | NA | ✓ |
| PR-9 | Pavement Management System | NA | ✓ |
| PR-10 | Site Maintenance Plan | NA | |
| PR-11 | Educational Outreach | NA | |
| | ***Environment and Water*** | | |
| EW-1 | Environmental Management System | 2 | ✓ |
| EW-2 | Runoff Flow Control | 3 | |
| EW-3 | Runoff Quality | 3 | |
| EW-4 | Stormwater Cost Analysis | 1 | |
| EW-5 | Site Vegetation | 3 | |
| EW-6 | Habitat Restoration | 3 | |
| EW-7 | Ecological Connectivity | 3 | |
| EW-8 | Light Pollution | 3 | |
| | ***Access and Equity*** | | |
| AE-1 | Safety Audit | 2 | |
| AE-2 | Intelligent Transportation Systems | 5 | |
| AE-3 | Context Sensitive Solutions | 5 | |
| AE-4 | Traffic Emissions Reduction | 5 | |
| AE-5 | Pedestrian Access | 2 | |
| AE-6 | Bicycle Access | 2 | |
| AE-7 | Transit & HOV Access | 5 | |
| AE-8 | Scenic Views | 2 | |
| AE-9 | Cultural Outreach | 2 | |
| | ***Construction Activities*** | | |
| CA-1 | Quality Management System | 2 | ✓ |
| CA-2 | Environmental Training | 1 | ✓ |
| CA-3 | Site Recycling Plan | 1 | ✓ |
| CA-4 | Fossil Fuel Reduction | 2 | ✓ |
| CA-5 | Equipment Emission Reduction | 2 | ✓ |
| CA-6 | Paving Emission Reduction | 1 | ✓ |
| CA-7 | Water Use Tracking | 2 | ✓ |
| CA-8 | Contractor Warranty | 3 | ✓ |
| | ***Materials and Resources*** | | |
| MR-1 | Lifecycle Assessment | 2 | ✓ |
| MR-2 | Pavement Reuse | 5 | ✓ |
| MR-3 | Earthwork Balance | 1 | |
| MR-4 | Recycled Materials | 5 | ✓ |
| MR-5 | Regional Materials | 5 | ✓ |
| MR-6 | Energy Efficiency | 5 | |
| | ***Pavement Technologies*** | | |
| PT-1 | Long-Life Pavement | 5 | ✓ |
| PT-2 | Permeable Pavement | 3 | ✓ |
| PT-3 | Warm-Mix Asphalt | 3 | ✓ |
| PT-4 | Cool Pavement | 5 | ✓ |
| PT-5 | Quiet Pavement | 3 | ✓ |
| PT-6 | Pavement Performance Tracking | 1 | ✓ |
| | **Total Points** | **108** | **53** |
| | **Percentage of points directly relevant to pavement** | | **49%** |

Table 10-4. Summary of ENVISION sustainability criteria and scoring (ISI and Zofnass 2012).

| Credit | Title | Points Possible | Pavement Related |
|---|---|---|---|
| | ***Quality of Life*** | | |
| QL1.1 | Improve Community Quality of Life | 25 | |
| QL1.2 | Stimulate Sustainable Growth and Development | 16 | |
| QL1.3 | Develop Local Skills and Capabilities | 15 | ✓ |
| QL2.1 | Enhance Public Health and Safety | 16 | ✓ |
| QL2.2 | Minimize Noise and Vibration | 11 | ✓ |
| QL2.3 | Minimize Light Pollution | 11 | |
| QL2.4 | Improve Community Mobility and Access | 14 | |
| QL2.5 | Encourage Alternative Modes of Transportation | 15 | |
| QL2.6 | Improve Accessibility, Safety and Wayfinding | 15 | |
| QL3.1 | Preserve Historic and Cultural Resources | 16 | |
| QL3.2 | Preserve Views and Local Character | 14 | |
| QL3.3 | Enhance Public Space | 13 | |
| | ***Leadership*** | | |
| LD1.1 | Provide Effective Leadership And Commitment | 17 | |
| LD1.2 | Establish A Sustainability Management System | 14 | |
| LD1.3 | Foster Collaboration And Teamwork | 15 | |
| LD1.4 | Provide for Stakeholder Involvement | 14 | |
| LD2.1 | Pursue By-Product Synergy Opportunities | 15 | ✓ |
| LD2.2 | Improve Infrastructure Integration | 16 | ✓ |
| LD3.1 | Plan for Long-Term Monitoring and Maintenance | 10 | ✓ |
| LD3.2 | Address Conflicting Regulations and Policies | 8 | |
| LD3.3 | Extend Useful Life | 12 | ✓ |
| | ***Resource Allocation*** | | |
| RA1.1 | Reduce Net Embodied Energy | 18 | ✓ |
| RA1.2 | Support Sustainable Procurement Practices | 9 | |
| RA1.3 | Use Recycled Materials | 14 | ✓ |
| RA1.4 | Use Regional Materials | 10 | ✓ |
| RA1.5 | Divert Waste from Landfills | 11 | ✓ |
| RA1.6 | Reduce Excavated Materials Taken Off Site | 6 | |
| RA1.7 | Provide for Deconstruction and Recycling | 12 | ✓ |
| RA2.1 | Reduce Energy Consumption | 18 | |
| RA2.2 | Use Renewable Energy | 20 | |
| RA2.3 | Commission and Monitor Energy Systems | 11 | |
| RA3.1 | Protect Fresh Water Availability | 21 | |
| RA3.2 | Reduce Potable Water Consumption | 21 | |
| RA3.3 | Monitor Water Systems | 11 | |
| | ***Natural World*** | | |
| NW1.1 | Preserve Prime Habitat | 18 | |
| NW1.2 | Preserve Wetlands and Surface Water | 18 | |
| NW1.3 | Preserve Prime Farmland | 15 | |
| NW1.4 | Avoid Adverse Geology | 5 | |
| NW1.5 | Preserve Floodplain Functions | 14 | |
| NW1.6 | Avoid Unsuitable Development on Steep Slopes | 6 | |
| NW1.7 | Preserve Greenfields | 23 | |
| NW2.1 | Manage Stormwater | 21 | ✓ |
| NW2.2 | Reduce Pesticides and Fertilizer Impacts | 9 | |
| NW2.3 | Prevent Surface and Groundwater Contamination | 18 | |
| NW3.1 | Preserve Species Biodiversity | 16 | |
| NW3.2 | Control Invasive Species | 11 | |
| NW3.3 | Restore Disturbed Soils | 10 | |
| NW3.4 | Maintain Wetland and Surface Water Functions | 19 | |

Table 10-4. Summary of ENVISION sustainability criteria and scoring (ISI and Zofnass 2012) (continued).

| Credit | Title | Points Possible | Pavement Related |
|---|---|---|---|
| | ***Climate and Risk*** | | |
| CR1.1 | Reduce Greenhouse Gas Emissions | 25 | ✓ |
| CR1.2 | Reduce Air Pollutant Emissions | 15 | ✓ |
| CR2.1 | Assess Climate Threat | 15 | |
| CR2.2 | Avoid Traps and Vulnerabilities | 20 | |
| CR2.3 | Prepare for Long-Term Adaptability | 20 | ✓ |
| CR2.4 | Prepare for Short-Term Hazards | 21 | |
| CR2.5 | Management Heat Island Effects | 6 | ✓ |
| | **Total Points** | **809** | **247** |
| | **Percentage of points directly relevant to pavement** | | **31%** |

Table 10-5. Summary of GreenLITES sustainability criteria and scoring (NYSDOT 2010).

| Credit | Title | Points Possible | Pavement Related |
|---|---|---|---|
| | ***Alignment Selection*** | | |
| S-1a | Avoidance of previously undeveloped lands (open spaces or "greenfields") | 2 | |
| S-1b | Selecting an alignment that establishes a minimum 100-ft (30.5-m) buffer zone | 2 | |
| S-1c | Alignments which minimize overall construction "footprint" | 2 | |
| S-1d | Design vertical alignments which minimize total earthwork | 1 | |
| S-1e | Adjust alignment to avoid or minimize impacts to social/environmental | 1 | |
| S-1f | Alignments that optimize benefits among competing constraints | 1 | |
| S-1g | Micro-adjustments that do not compromise safety or operation | 1 | |
| S-1h | Clear zones seeded with seed mixtures that help to reduce maintenance | 1 | |
| S-1i | Provide a depressed roadway alignment | 1 | |
| S-1j | Use of launched soil nails as a more cost effective option to stabilize a slope | 1 | |
| | ***Context Sensitive Solutions*** | | |
| S-2a | Adjust or incorporate highway features to respond to the unique character | 2 | |
| S-2b | Incorporate local or natural materials for substantial visual elements | 2 | |
| S-2c | Visual enhancements (screening objectionable views) | 2 | |
| S-2d | Period street furniture/lighting/appurtenances. | 1 | |
| S-2e | Inclusion of visually-contrasting (colored or textured) pedestrian | 1 | |
| S-2g | Incorporates guidance from Section 23 - Aesthetics of the NYS Bridge | 1 | |
| S-2h | Site materials selection & detailing to reduce overall urban "heat island" effect | 1 | |
| S-2i | Permanently protect viewsheds via environmental or conservation easements | 1 | |
| S-2j | Color anodizing of aluminum elements (ITS cabinets, non-decorative light | 1 | |
| S-2k | Decorative bridge fencing (in lieu of standard chain link). | 1 | |
| S-2l | Use of concrete form liners (for bridge approach barriers, parapet walls, etc.) | 1 | |
| S-2m | Imprinted concrete/asphalt mow strips, gores or snow storage areas | 1 | ✓ |
| | ***Land Use/Community Planning*** | | |
| S-3a | Use of more engaging public participation techniques (e.g., charette, task force) | 2 | |
| S-3b | Enhanced outreach efforts (e.g., newsletters, project-specific Web page | 2 | |
| S-3c | Projects better enabling use of public transit (e.g., bus shelters, 'Park &Ride') | 2 | |
| S-3d | Projects applying "Walkable Communities" or "Complete Streets" | 2 | |
| S-3e | Projects that increase transportation efficiencies for moving freight | 2 | |
| S-3f | Project-specific formal agreement with public or private entities | 2 | |
| S-3g | Project is consistent with local and regional plans | 2 | |
| S-3h | Project reports and community outreach materials available online | 1 | |
| S-3j | Establishment of a new recreational access facility (e.g., trailhead parking) | 2 | |
| S-3k | Establishment of a new recreational facility (pocket park, roadside overlook) | 2 | |
| S-3l | Enhancement of an existing recreational facility | 1 | |
| | ***Protect, Enhance or Restore Wildlife Habitat*** | | |
| S-4a | Mitigation of habitat fragmentation | 3 | |
| S-4b | Providing for enhancements to existing wildlife habitat (e.g., bird/bat houses) | 2 | |
| S-4c | Partial mitigation of habitat fragmentation through techniques | 2 | |
| S-4d | Use of natural-bottomed culverts | 2 | |
| S-4e | Wildlife crossings that are structures that allow for safe passage of wildlife | 2 | |
| S-4f | Wetland restoration, enhancement, or establishment | 2 | |
| S-4g | Minimize use of lands that are part of a significant contiguous wildlife habitat | 1 | |
| S-4h | Use of wildlife mortality reduction measures | 1 | |
| S-4k | Stream restoration/enhancement | 1 | |
| S-4l | Installation of mowing markers to protect natural areas and wetlands | 1 | |
| S-4m | Inclusion of scheduling and logistic requirements to avoid disrupting wildlife | 1 | |
| S-4n | Permanently protects the new or expanded habitat | 1 | |

Table 10-5. Summary of GreenLITES sustainability criteria and scoring (NYSDOT 2010) (continued).

| Credit | Title | Points Possible | Pavement Related |
|---|---|---|---|
| | ***Protect, Plant or Mitigate for Removal of Trees & Plant Communities*** | | |
| S-5a | Avoidance/protection of established trees/veg communities | 2 | |
| S-5b | Designs that demonstrate a net increase in tree canopy | 2 | |
| S-5c | Re-establishment or expansion of native vegetation into reclaimed work areas | 2 | |
| S-5d | Use of trees, large shrubs or other suitable vegetation as living snow fences | 2 | |
| S-5e | Use of native species for seed mixtures and other plantings | 1 | |
| S-5f | Avoidance/protection of individual significant trees/desired vegetation | 1 | |
| S-5g | Designs that demonstrate no net loss of tree canopy or mitigation | 1 | |
| S-5h | Planting trees, shrubs or plant material in lieu of traditional turf grass | 1 | |
| S-5i | Removal of undesirable plant species | 1 | |
| S-5j | Preserving, replacing, or enhancing vegetation associated with historic property | 1 | |
| | ***W-1 Stormwater Management (Volume & Quality)*** | | |
| W-1a | Improve water quality or nearby habitat | 2 | |
| W-1b | Detecting and eliminating any non-stormwater discharges | 2 | |
| W-1c | Demonstrate a reduction of pollutant loadings to adjacent water sources | 2 | |
| W-1d | Reduction in overall impervious area | 2 | |
| W-1f | Requirements for staged construction to minimize bare soil exposure | 1 | |
| W-1g | Detecting/documenting non-stormwater discharges from unpermitted sources | 1 | |
| | ***W-2 Best Management Practices (BMPs)*** | | |
| W-2a | Design features that make use of highly permeable soils | 2 | |
| W-2b | Use of other structural BMPs (e.g., wet or dry swales, sand filters, filter bags) | 2 | |
| W-2c | Inclusion of “permeable pavement” such as grid pavers where practical | 2 | ✓ |
| W-2d | Minimize the project's overall impervious surface area increase | 1 | |
| W-2e | Include grass channels, where appropriate | 1 | |
| W-2f | Designate qualified environmental construction monitor to provide oversight | 2 | |
| | ***M-1 Reuse of Materials*** | | |
| M-1a | Specify that 75 percent or more of topsoil removed for grading is reused on site | 2 | |
| M-1b | Design the project so that “cut-and-fills” are balanced to within 10 percent | 2 | |
| M-1c | Reuse of excess fill (“spoil”) within the project corridor | 2 | |
| M-1d | Specify rubblizing or crack and seating of portland cement concrete | 2 | ✓ |
| M-1e | Reuse of previous pavement as subbase during full-depth reconstruction | 2 | ✓ |
| M-1f | Arranging for the reuse of excavated material, asphalt millings, old concrete | 2 | ✓ |
| M-1g | Specify the processing of demolished concrete to reclaim scrap metals | 2 | ✓ |
| M-1h | Salvaging removed trees for lumber or similar uses | 2 | |
| M-1i | Use surplus excavated material on nearby state highways for slope flattening | 2 | |
| M-1j | Use surplus excavated material, demolished concrete, or millings at nearby abandoned quarry | 2 | |
| M-1k | Specify that 50 percent or more of topsoil removed for grading is reused on site | 1 | |
| M-1l | Design the project so that cut and fills are balanced to within 25 percent | 1 | |
| M-1m | Reuse (i.e., remove and reset versus remove and replace) of granite curbing | 1 | |
| M-1n | Reuse of elements of the previous structure (stone veneer, decorative railing) | 1 | |
| M-1o | Designing an on-site location for chipped wood waste disposal | 1 | |
| M-1p | Specifying the recycling of chipped untreated wood waste for use as mulch | 1 | |
| M-1q | Project documents make scrap metals available for reuse or recycling | 1 | |
| M-1r | Identify approved, environmentally acceptable and permitted sites for disposal | 1 | |
| M-1s | Obtain and implement a project specific DEC Beneficial Use Determination for re-use of otherwise waster material from a location with New York State | 1 | |
| M-1t | Specify the salvage/moving of houses rather than demo for disposal in landfill | 1 | |
| M-1u | Reuse of major structural elements such as bridge piers, bridge structure, etc. | 2 | |

Table 10-5. Summary of GreenLITES sustainability criteria and scoring (NYSDOT 2010) (continued).

| Credit | Title | Points Possible | Pavement Related |
|---|---|---|---|
| | ***M-2 Recycled Content*** | | |
| M-2a | Use tire shreds in embankments | 2 | |
| M-2b | Use recycled plastic extruded lumber or recycled tire rubber | 2 | |
| M-2c | Specify hot-in-place or cold-in-place recycling of hot-mix asphalt pavements | 2 | ✓ |
| M-2d | Specify use of recycled glass in pavements and embankments | 2 | ✓ |
| M-2e | Specify asphalt pavement mixtures containing recycled asphalt pavement | 2 | ✓ |
| M-2f | Specify PCC pavement mixtures containing recycled concrete aggregate | 2 | ✓ |
| M-2g | Use crumb rubber or recycled plastic for noise barrier material | 2 | ✓ |
| M-2h | Use of porous pavement systems in light duty situations (e.g., sidewalks) | 2 | ✓ |
| | ***M-3 Local Materials*** | | |
| M-3a | Specify locally available natural light weight fill | 2 | |
| M-3b | Specify local seed stock and plants | 2 | |
| | ***M-4 Bio-engineering Techniques*** | | |
| M-4a | Project designs that utilize soil bioengineering treatments | 2 | |
| M-4b | Project designs utilizing soil biotechnical engineering treatments | 2 | |
| M-4c | Projects using targeted biological control methods to reduce invasive species | 2 | |
| M-4d | Project designs utilizing soil biotechnical engineering treatments | 1 | |
| M-4e | Project designs that utilize soil bioengineering/soil biotechnical treatments | 1 | |
| | ***M-5 Hazardous Material Minimization*** | | |
| M-5a | Project design substantially minimizes the need to use hazardous materials | 2 | |
| M-5b | Project design specifies less hazardous materials or avoids their generation | 2 | |
| M-5c | Removing and disposing of contaminated soils | 2 | |
| | ***E-1 Improved Traffic Flow*** | | |
| E-1a | Special use lane (HOV/Reversible/Bus Express) | 3 | |
| E-1b | Innovative interchange design or elimination of freeway bottlenecks | 3 | |
| E-1c | Specify new roundabout(s) | 3 | |
| E-1d | Implementation of Traffic Management Center / Traveler Information System | 3 | |
| E-1e | Installation of a closed-loop coordinated signal system | 2 | |
| E-1f | Installation of a transit express system (queue jumper, pre-emptive signals, etc.) | 2 | |
| E-1g | Expansion of a Traffic Management Center / Traveler Information System | 2 | |
| E-1h | Implementation of a corridor-wide access management plan | 2 | |
| E-1i | Limiting/consolidating access points along highway | 1 | |
| E-1j | Improving a coordinated signal system and other signal timing and detection | 1 | |
| E-1k | Adding bus turnouts | 1 | |
| E-1l | Installing higher capacity controllers to improve flow/reduce delay | 1 | |
| E-1m | Infill or preparation for Traffic Management/Traveler Information System | 1 | |
| E-1n | Inclusion of integrated traffic/incident management/traveler information system | 1 | |
| E-1o | Installation of isolated systems to provide for spot warning | 1 | |
| E-1p | Road Diet (reduction in lanes to add turn lane & accommodate bike traffic) | 2 | |
| | ***E-2 Reduce Electrical Consumption*** | | |
| E-2a | Solar/battery powered street lighting or warning signs | 2 | |
| E-2b | Replace overhead sign lighting with higher type retro-reflective sign panels | 2 | |
| E-2c | Use of LED street lighting | 2 | |
| E-2d | Solar bus stops | 2 | |
| E-2e | Use of LED warning signs/flashing beacons | 1 | |
| E-2e | Retrofit existing street/sign lighting with high efficiency types | 1 | |
| | ***E-3 Reduce Petroleum Consumption*** | | |
| E-3a | Provide new Park & Ride lots | 3 | |
| E-3b | Provide new intermodal connections | 3 | |
| E-3c | Increase bicycle amenities at Park & Rides and transit stations | 2 | |

Table 10-5. Summary of GreenLITES sustainability criteria and scoring (NYSDOT 2010) (continued).

| Credit | Title | Points Possible | Pavement Related |
|---|---|---|---|
| E-3e | Operational improvements of an existing Park & Ride lot | 1 | |
| E-3f | Improve an existing intermodal connection | 1 | |
| E-3g | Reduce mowing areas outside of the clear zone | 1 | |
| E-3h | Use of warm-mix asphalt | 1 | ✓ |
| E-3i | Documented analysis proving the project design reduced carbon footprint | 1 | ✓ |
| E-3j | Documented analysis proving the work zone requires the least fuel usage | 1 | ✓ |
| E-3k | Improved shading through vegetation at Park & Ride lots to reduce UHI | 1 | |
| | ***E-4 Improve Bicycle & Pedestrian Facilities*** | | |
| E-4a | New grade-separated (bridge or underpass) bike/pedestrian crossing structure | 3 | |
| E-4b | Separate bike lane at intersection | 2 | |
| E-4c | New separated bike path or shoulder widening to provide for on-road bike lane | 2 | |
| E-4d | Create new or extend existing sidewalks | 2 | |
| E-4e | New pedestrian signals | 2 | |
| E-4f | Align roadway and other highway features/structures within ROW for future development | 2 | |
| E-4g | Work with local communities to create parallel bike routes | 2 | |
| E-4h | Sidewalk or bikeway rehabilitation, widening, realignment or repair | 1 | |
| E-4i | Upgrading pedestrian signals | 1 | |
| E-4j | Installation of bikeway signs, "Share the Road" signs, or shared lanes markings | 1 | |
| E-4k | Shoulder restoration for bicycling | 1 | |
| E-4l | Inclusion of five-rail bridge rail system for bicyclists | 1 | |
| E-4m | Installation of permanent bicycle racks | 1 | |
| E-4n | New crosswalks | 1 | |
| E-4o | New curb bulb-outs | 1 | |
| E-4p | New raised medians/pedestrian refuge islands | 1 | |
| E-4q | New speed hump/speed table/raised intersection | 1 | |
| E-4r | New curbing (where none previously existed), to better define the edge of road | 1 | |
| E-4s | New or relocated highway barrier or repeating vertical elements | 1 | |
| E-4t | Installation of bicycle detectors (quadrupoles) at signalized intersections | 1 | |
| E-4u | "All Stop" phase programmed into a traffic signal | 1 | |
| E-4v | Permanent digital "Your Speed is XX" radar speed reader signs | 1 | |
| E-4w | Overhead flashing beacon, lighted "Crosswalk" sign, or pedestrian signal | 1 | |
| E-4x | Advanced warning of crosswalk with signs and yield pavement markings | 1 | |
| E-4y | In street plastic pylon "State Law - Yield to Pedestrians within Crosswalk" sign | 1 | |
| E-4z | Use of durable cast iron detectible warning units embedded in concrete | 1 | |
| E-4aa | Add/replace crosswalks with high visibility cross walks | 1 | |
| | ***E-5 Noise Abatement*** | | |
| E-5a | Construction of a new noise barrier | 2 | |
| E-5b | Incorporate traffic system management techniques to reduce prior noise | 2 | |
| E-5c | Provide a buffer zone for adjacent receptors | 2 | |
| E-5d | Provide sound insulation to public schools | 2 | |
| E-5e | Diamond grinding of existing portland cement concrete (PCC) pavement | 1 | ✓ |
| E-5f | Rehabilitation of an existing noise wall | 1 | |
| E-5g | Berms designed to reduce noise | 1 | |
| E-5h | Provide planting to improve perceived noise impacts | 1 | |
| | ***E-6 Stray Light Reduction*** | | |
| E-6a | Retrofit existing light heads with full cut-offs | 2 | |
| E-6c | Use cut-offs on new light heads | 1 | |
| | **Total Points** | **271** | **27** |
| | **Percentage of points directly relevant to pavement** | | **10%** |

Table 10-6. Summary of LEED-ND sustainability criteria and scoring (USGBC 2012; 2013).

| Credit | Title | Points Possible | Pavement Related |
|---|---|---|---|
| | ***Smart Location and Linkage*** | | |
| SLLp1 | Smart Location | NA | |
| SLLp2 | Imperiled Species and Ecological Communities | NA | |
| SLLp3 | Wetland and Water Body Conservation | NA | |
| SLLp4 | Agricultural Land Preservation | NA | |
| SLLp5 | Floodplain Avoidance | NA | |
| SLLc1 | Preferred Locations | 10 | |
| SLLc2 | Brownfield Development | 2 | |
| SLLc3 | Access to Quality Transit | 7 | |
| SLLc4 | Bicycle Facilities | 2 | |
| SLLc5 | Housing and Jobs Proximity | 3 | |
| SLLc6 | Steep Slope Protection | 1 | |
| SLLc7 | Site Design for Habitat or Wetland and Water Body Conservation | 1 | |
| SLLc8 | Restoration of Habitat or Wetlands and Water Bodies | 1 | |
| SLLc9 | Long-Term Conservation Management of Habitat or Wetlands and Water Bodies | 1 | |
| | ***Neighborhood Pattern and Design*** | | |
| NPDp1 | Walkable Streets | NA | |
| NPDp2 | Compact Development | NA | |
| NPDp3 | Connected and Open Community | NA | |
| NPDc1 | Walkable Streets | 9 | |
| NPDc2 | Compact Development | 6 | |
| NPDc3 | Mixed-Use Neighborhoods | 4 | |
| NPDc4 | Housing Types and Affordability | 7 | |
| NPDc5 | Reduced Parking Footprint | 1 | |
| NPDc6 | Connected Circulation Network | 2 | |
| NPDc7 | Transit Facilities | 1 | |
| NPDc8 | Transportation Demand Management | 2 | |
| NPDc9 | Access to Civic and Public Spaces | 1 | |
| NPDc10 | Access to Recreational Facilities | 1 | |
| NPDc11 | Visitability and Universal Design | 1 | |
| NPDc12 | Community Outreach and Involvement | 2 | |
| NPDc13 | Local Food Production | 1 | |
| NPDc14 | Tree-Lined and Shaded Streetscapes | 2 | |
| NPDc15 | Neighborhood Schools | 1 | |
| | ***Green Infrastructure and Buildings*** | | |
| GIBp1 | Certified Green Building | NA | |
| GIBp2 | Minimum Building Energy Performance | NA | |
| GIBp3 | Indoor Water Use Reduction | NA | |
| GIBp4 | Construction Activity Pollution Prevention | NA | ✓ |
| GIBc1 | Certified Green Buildings | 5 | |
| GIBc2 | Optimize Building Energy Performance | 2 | |
| GIBc3 | Indoor Water Use Reduction | 1 | |
| GIBc4 | Outdoor Water Use Reduction | 2 | |
| GIBc5 | Building Reuse | 1 | |
| GIBc6 | Historic Resource Preservation and Adaptive Use | 2 | |
| GIBc7 | Minimize Site Disturbance | 1 | |
| GIBc8 | Rainwater Management | 4 | ✓ |
| GIBc9 | Heat Island Reduction | 1 | ✓ |
| GIBc10 | Solar Orientation | 1 | |
| GIBc11 | Renewable Energy Production | 3 | |
| GIBc12 | District Heating and Cooling | 2 | |
| GIBc13 | Infrastructure Energy Efficiency | 1 | |
| GIBc14 | Wastewater Management | 2 | |
| GIBc15 | Recycled and Reused Infrastructure | 1 | ✓ |
| GIBc16 | Solid Waste Management | 1 | |
| GIBc17 | Light Pollution Reduction | 1 | |
| | **Total Points** | **100** | **6** |
| | **Percentage of points directly relevant to pavement** | | **6%** |

## Use of Assessment Methods

Agencies that use the various assessment methods tend to do so by choice because they recognize a benefit in doing so. A general discussion on the use of these different methods is presented in the following sections.

### Use Depends on Owner/Agency and Project Priorities

LCCA, LCA, and rating systems can be used alone or in concert to measure sustainability. In general, using them in concert provides a more holistic assessment of sustainability since each system tends to either (1) address one specific component of sustainability in detail, or (2) address all components in less detail. Ultimately, the priorities of the owner/agency and the characteristics of the project, as well as the desired outcomes viewed within the context of larger systems, should determine what assessment methods are used and what priority is given to each. For instance, a desire to implement lowest life-cycle solutions has driven many state DOTs to use LCCA in their pavement type selection process for major projects. On the other hand, a statewide GHG reduction goal may make it sensible to use LCA as a pavement system metric both for accounting and process improvement purposes. Or, a strategic DOT goal to improve or communicate sustainability (however the DOT chooses to define it) may make it sensible to use a rating system that takes a broad view of sustainability. As a footnote to this, it is worth noting that some rating systems require the use of LCCA and LCA within their framework.

### Application at Various Levels

Goals for addressing sustainability can be defined on an agency level, on a pavement system level, and on a pavement project level. The types of sustainability performance tools described in this chapter can be used and tailored to address these different goals. Figure 10-7 provides a schematic of how LCCA, LCA, and rating systems can be applied at these different levels.

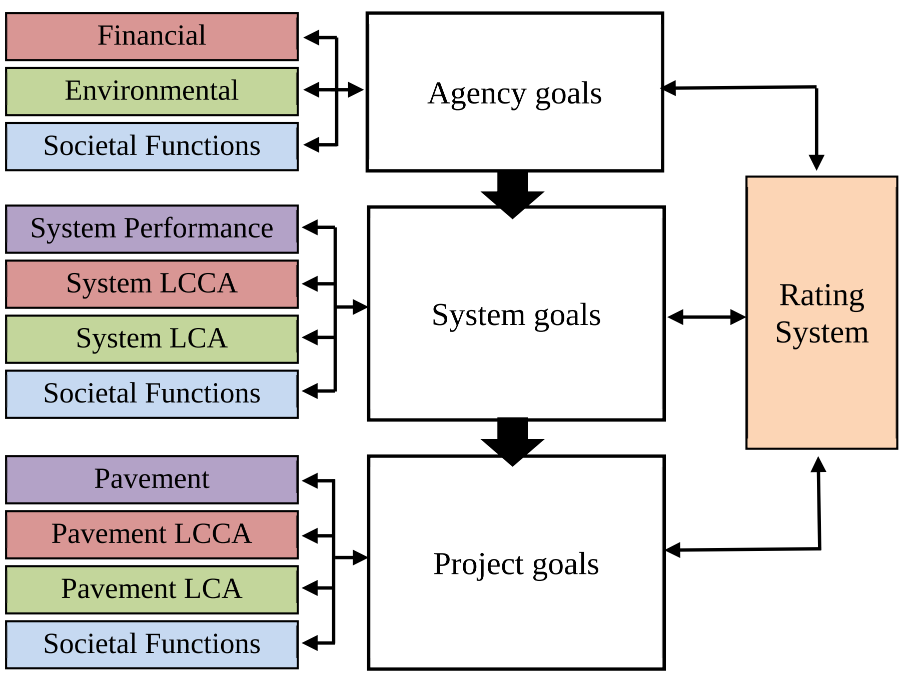



Figure 10-7. Assessing sustainabilty with LCCA, LCA, and rating systems on different levels.

It can be seen in figure 10-7 that rating systems aim to be more comprehensive in terms of topics that are covered and they typically include requirements on all levels. It also shows that LCCA and LCA can be applied at different levels. Through all of this, it is important to understand that the LCCA and LCA applications at the different levels are different types of studies; that is, depending on the specific goals and questions to be addressed the right use can be defined. As a general rule of thumb, system LCAs tend to be more generic and pavement LCAs tend to be more specific.

### Level of Standardization

Currently, LCCA is the most mature of the three assessment methods in the pavement industry. Guidance from Walls and Smith (1998) has been generally accepted by the industry and incorporated into numerous official methods and software, the most prominent of which is *RealCost*.

LCA has a commonly accepted standard method (delineated by ISO 14040 and 14044); however, specifics within this method vary greatly from one application to another. Attempts at standardization within the pavement industry are underway (e.g., UCPRC 2010), but it may be some time before LCA reaches the same level of standardization that LCCA has in the pavement industry.

Rating systems are relatively new to the pavement industry and are not subject to any standard method. The more mature ones that are beginning to be used in practice generally focus on transportation infrastructure as a whole rather than just specifically on pavements. These tend to address some of the same core pavement sustainability concepts; however, there are differences and exclusions that should be investigated.

## Concluding Remarks

Pavement sustainability can be evaluated using several different methods or tools, including performance assessment, life-cycle cost analysis, life-cycle assessment, and pavement rating systems. This chapter focuses on the latter three items, and describes the basis, inherent assumptions, and overall capabilities and limitations of each approach. Specifically:

- LCCA is an analysis technique that uses economic analysis to evaluate the total cost of an investment option over its entire life (Walls and Smith 1998). As such, it is principally used to address the economic component of sustainability.
- LCA is a technique that can be used for analyzing and quantifying the environmental impacts of a product, system, or process. It focuses on the environmental impacts throughout the pavement life cycle (from raw material acquisition to final disposal).
- Sustainability rating systems are essentially a list of sustainability best practices with an associated common metric (typically points). Rating systems are one way of quantifying the diverse set of sustainability best practices.

These methods can be used independently or in concert to quantify various aspects of sustainability, but ultimately, the priorities of the owner/agency and the characteristics of the project, as well as the desired outcomes viewed within the context of larger systems will determine which approach (or set of approaches) is most appropriate. It is important to note that there are currently few, if any, generally accepted metrics able to measure equity/social impacts associated with pavement systems.

## References

American Concrete Pavement Association (ACPA). 2011. *Life-Cycle Cost Analysis: A Tool for Better Pavement Investment and Engineering Decisions.* Engineering Bulletin EB011. American Concrete Pavement Association, Rosemont, IL.

Argonne National Laboratory (ANL). 2013. *GREET Life-Cycle Model*. Argonne National Laboratory, U.S. Department of Energy, Lemont, IL. (Web Link).

Athena Sustainable Materials Institute (Athena). 2013. *Impact Estimator for Highways: User Guide*. Athena Sustainable Materials Institute, Ottawa, Ontario, Canada. (Web Link).

Ayer, N. W., P. H. Tyedmers, N. L. Pelletier, U. Sonesson, and A. Scholz. 2007. "Co-Product Allocation in Life Cycle Assessments of Seafood Production Systems: Review of Problems and Strategies." *International Journal of Life Cycle Assessment.* Vol. 12, Issue 7. Springer Science+Business Media, Berlin, Germany.

Bare, J. 2011. "TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0." *Clean Technologies and Environmental Policy*. 13(5). Springer.

Basset-Mens, C. and H. M. G. van der Werf. 2005. "Scenario-Based Environmental Assessment of Farming Systems: The Case of Pig Production in France." *Agriculture, Ecosystems and Environment*. Vol. 105, Issues 1-2. Elsevier, Philadelphia, PA.

Bernard, F., T. Blomberg, and M. Southern. 2012. "Life Cycle Inventory: Bitumen." *International Symposium on Life Cycle Assessment and Construction.* Nantes, France.

Bevan, T., L. Reid, A. Davis, T. Neuman, K. Penney, S. Seskin, M. VanZerr, J. Anderson, S. Muench, C. Weiland, T. Ramani, J. Zietsman, J. Crossett, C. Crocker, and J. Schulz. 2012. *INVEST: Sustainable Highways Self-Evaluation Tool*. Version 1.0. Federal Highway Administration, Washington, DC. (Web Link).

California Department of Transportation (Caltrans). 2011. *Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS): Caltrans "Rapid Rehab" Software.* California Department of Transportation, Sacramento, CA.

Carbon Leadership Forum. 2010. *Product Category Rules, CPC Class 3744, Cement*. PCR 2010-09, Version 1.0. Carbon Leadership Forum, University of Washington, Seattle, WA. (Web Link).

Carbon Leadership Forum. 2013. *Product Category Rules (PCR) for ISO 14025 Type III Environmental Product Declarations (EPDs) of Concrete*. Revised Version 1.1. Carbon Leadership Forum, University of Washington, Seattle, WA. (Web Link).

CEN. 2012. *Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products*. EN 15804:2012. British Standards Institution, UK.

Embacher, R. and M. Snyder. 2001. "Life Cycle Cost Comparisons of Asphalt and Concrete Pavements on Low-Volume Roads." *Transportation Research Record 1749*. Transportation Research Board, Washington, DC.

Environmental Protection Agency (EPA). 2005. *User's Guide for the Final NONROAD2005 Model*. EPA420-R-05-013. U.S. Environmental Protection Agency, Washington, DC. (Web Link).

Environmental Protection Agency (EPA). 2012a. *Motor Vehicle Emission Simulator (MOVES): User Guide for MOVES2010b. EPA-420-B-12-001b*. Environmental Protection Agency, Washington, DC. (Web Link).

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

Federal Highway Administration (FHWA). 2002. *Life-Cycle Cost Analysis Primer*. FHWA-IF-02-047. Federal Highway Administration, Washington, DC. (Web Link).

Federal Highway Administration (FHWA). 2004. *Life-Cycle Cost Analysis: RealCost User Manual*. RealCost Version 2.1. Federal Highway Administration, Washington, DC. (Web Link).

Federal Highway Administration (FHWA). 2010. *Life-Cycle Cost Analysis: RealCost User Manual*. RealCost Version 2.5. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). 2011. *Sustainable Highways Self-Evaluation Tool: Compendium of System Planning and Processes, Project Delivery and Operations and Maintenance Criteria—Pilot Test Version*. Federal Highway Administration, Washington, DC. (Web Link).

Federal Highway Administration (FHWA). 2012. *Use of Alternate Bidding for Pavement Type Selection.* Technical Advisory T 5040.39. Federal Highway Administration, Washington, DC. (Web Link).

Federal Highway Administration (FHWA). 2013. *Improving Transportation Investment Decisions through Life-Cycle Cost Analysis.* Federal Highway Administration, Washington, DC. (Web Link).

Gallivan, F., J. Ang-Olson, and A. Papson. 2010. *Greenhouse Gas Mitigation Measures for Transportation Construction, Maintenance, and Operations Activities*. Final Report. NCHRP Project 25-25(58). Transportation Research Board, Washington DC. (Web Link).

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

Hallin, J. P., S. Sadaslvam, J. Mallela, D. K. Hein, M. I. Darter, and H. L. Von Quintus. 2011. *Guide for Pavement Type Selection*. NCHRP Report 703. Transportation Research Board, Washington, DC.

Hicks, R. G. and J. A. Epps. 1996. *Life-Cycle Costs for Asphalt-Rubber Paving Materials.* RPA Reports. Rubber Pavements Association, Tempe, AZ. (Web Link).

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

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

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

Institute for Sustainable Infrastructure (ISI) and Zofnass Program for Sustainable Infrastructure at the Harvard University Graduate School of Design (Zofnass). 2012. *Envision, Version 2.0. A Rating System for Sustainable Infrastructure*. ISI, Washington, DC. (Web Link).

Muench, S. T., J. L. Anderson, J. P. Hatfield, J. R. Koester, and M. Söderlund. 2011. *Greenroads Manual*. Vol. 1.5. University of Washington, Seattle, WA. (Web Link).

Mukherjee, A., B. Stawowy, and D. Cass. 2013. "Project Emission Estimator: Tool for Contractors and Agencies for Assessing Greenhouse Gas Emissions of Highway Construction Projects." *Transportation Research Record 2366*. Transportation Research Board, Washington, DC.

National Cooperative Highway Research Program (NCHRP). 2004. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. Transportation Research Board, Washington, DC.

National Highway Institute (NHI). 2008. *Fundamentals of Life-Cycle Cost Analysis – NHI Course No. 13113. Participant Workbook.* FHWA-NHI-09-024. National Highway Institute, Arlington, VA.

New York State Department of Transportation (NYSDOT). 2010. *GreenLITES Project Design Certification Program*, Version 2.1.0. New York State Department of Transportation, Albany, NY. (Web Link).

New York State Department of Transportation (NYSDOT). 2012. *2012 GreenLITES Draft Operations Certification Program*. New York State Department of Transportation, Albany, NY. (Web Link).

Office of Management and Budget (OMB). 2012. *Memorandum for Chief Financial Officers and Agency Budget Directors: Interpretation of OMB Circular A-94*. Office of Management and Budget, Washington, DC. (Web Link).

Ram, P., T. Van Dam, J. Meijer, and K. Smith. 2011. *Sustainable Recycled Materials for Concrete Pavements*. Michigan Department of Transportation, Lansing, MI.

Riggs, J. L. and T. M. West. 1986. *Essentials of Engineering Economics*. 3rd Edition. McGraw-Hill Publishing, New York, NY.

Santero, N., E. Masanet, and A. Horvath. 2010. *Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research*. PCA R&D Serial No. SN3119a. Portland Cement Association, Skokie, IL.

Tulacz, G. J. 2013. "The Top 100 Green Contractors." *Engineering News-Record.* Vol. 271, No. 8. McGraw-Hill, New York, NY.

U.S. Green Building Council (USGBC). 2012. *LEED 2009 for Neighborhood Development*. U.S. Green Building Council, Washington, DC. (Web Link).

U.S. Green Building Council (USGBC). 2013. *USGBC Website*. U.S. Green Building Council, Washington, DC. (Web Link).

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

Van Leest, A., S. Van Hartskamp, and J. Meijer. 2008. "Decision Support Model for Road Pavements Based on Whole Life Costing, Life Cycle Assessment and Multi-Criteria Analysis." *Proceedings, 9th International Conference on Concrete Pavements*, San Francisco, CA.

Walls, J. and M. R. Smith. 1998. *Life-Cycle Cost Analysis in Pavement Design*. Interim Technical Bulletin. FHWA-SA-98-079. Federal Highway Administration, Washington, DC. (Web Link).

Wang, T., I. S. Lee, J. Harvey, A. Kendall, E. B. Lee, and C. Kim. 2012. *UCPRC Life Cycle Assessment Methodology and Initial Case Studies for Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance*. Research Report UCD-ITS-RR-12-36. California Department of Transportation, and University of California, Davis and Berkeley. (Web Link).

Weidema, B. P. 2001. "Avoiding Co-Product Allocation in Life-Cycle Assessment." *Journal of Industrial Ecology*. Vol. 4, No. 3. John Wiley and Sons, New York, NY.

West, R., N. Tran, M. Musselman, J. Skolnick, and M. Brooks. 2012. *A Review of the Alabama Department of Transportation's Policies and Procedures for LCCA for Pavement Type Selection.* NCAT Report 13-06. National Center for Asphalt Technology, Auburn, AL.