# CHAPTER 2. CONCEPTS OF PAVEMENT SUSTAINABILITY

This chapter introduces the basic concepts of sustainability as they relate to pavements. It includes discussions on (1) the definition of sustainability and its implications, (2) the role of pavements in sustainability, (3) the pavement life cycle, (4) different ways of measuring sustainability, and (5) an introduction to the framework used in this document for considering potential sustainability trade-offs.

## Sustainability Defined

In a broad sense, the "sustainability" of a human-devised system refers to its ability to (1) exist and function within a larger system without degrading it, and (2) provide for and meet the human needs for which the system was developed. There are a number of popular definitions of sustainability, but as described in chapter 1 these often start with the short definition issued by the World Commission on Environment and Development (WCED 1987):

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

And, as also noted in chapter 1, most sustainability definitions also reference three discrete components (environmental, social, and economic) that are to be considered; however, they usually do not direct how those components are to be prioritized beyond generally stating that they should be "balanced" without offering much direction on the definition of "balanced" or how such balancing is to occur.

This document uses a sustainability definition that is consistent with and complementary to the approach described in the *National Cooperative Highway Research Program (NCHRP) Report 708: A Guidebook for Sustainability Performance Measurement for Transportation Agencies* (Zietsman et al. 2011).[1] This approach emphasizes the underlying sustainability principles as the basis for guidance, with the actual definition being of secondary importance. Thus, "sustainable" in the context of pavements refers to system characteristics that encompasses a pavement's ability to (1) achieve the engineering goals for which it was constructed, (2) preserve and (ideally) restore surrounding ecosystems, (3) use financial, human, and environmental resources economically, and (4) meet basic human needs such as health, safety, equity, employment, comfort, and happiness.

***Sustainable Pavements Should:***

- ✓ *Achieve the engineering goals for which they were constructed.*
- ✓ *Preserve and (ideally) restore surrounding ecosystems.*
- ✓ *Use financial, human, and environmental resources economically.*
- ✓ *Meet human needs such as health, safety, equity, employment, comfort, and happiness.*

[1] This approach has also been adopted by other highway sustainability efforts, including NCHRP Project 20-83(07), *Sustainable Transportation Systems and Sustainability as an Organizing Principle in Transportation Agencies*. It is also complimentary to the FHWA's *Infrastructure Voluntary Evaluation Sustainability Tool* (INVEST).

**Sustainability Direction at the Federal Level: Executive Order 13514**

*Presidential Executive Order (EO) 13514, "Federal Leadership in Environmental, Energy, and Economic Performance" expands on EO 13423, "Strengthening Federal Environmental, Energy, and Transportation Management" in order to, "…establish an integrated strategy towards sustainability in the Federal Government and to make reduction of GHG a priority for Federal agencies." EO 13514 states, "'sustainability' and 'sustainable' mean to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generation…" (Bush 2007; Obama 2009). This executive order constitutes direction from the President to various Federal Agencies on how they are to be "sustainable." While its specific definition of "sustainability" is important, it is most significant because it sets specific targeted requirements for Federal agencies including reductions in GHG emissions, petroleum consumption, water use, and waste.*

*EO 13514's definition of "sustainability" is a paraphrasing of the United Nations 1987 Report of the World Commission on Environment and Development (commonly called the Brundtland Commission Report), in which sustainable development is defined as "…meeting the needs of the present without compromising the ability of future generations to meet their own needs…" (WCED 1987).*

## The Sustainability Continuum

As defined here, a "sustainable pavement" is, at present, an aspirational goal. That is, it is unlikely any pavement system based on current knowledge and technology could satisfy all or even most of the characteristics in the previous sustainability definition. However, continual improvement with an emphasis on each of these characteristics leads to more sustainable pavements, and, ultimately, to pavements that actually meet the rather demanding standards of sustainability. Progress towards sustainability may at first mean reducing bad outcomes (e.g., less pollution, reduced extraction of non-renewable resources, less waste). Further progress would transition to achieving a pavement system that is essentially a neutral player in the larger and surrounding systems (i.e., it does no harm). Importantly, however, progress should continue so that the pavements could ultimately produce positive outcomes (e.g., pavements that produce more energy than they consume, construction that restores more land than it uses). Current efforts at reducing the impact or amount of bad outcome and improving efficiency should be viewed as good transitional strategies on the long path towards the ultimate goal of producing only positive outcomes. This interpretation of sustainability is substantially different, and ultimately more positive, than one limited to reducing negative outcomes.

## Sustainable Best Practices

Recognizing the aspirational nature of a truly "sustainable pavement," this document highlights processes, actions, and features that advance the state of the practice towards more sustainable pavements rather than those that actually achieve the definition. Specifically, "sustainable best practices" are those practices that work to either (1) go above and beyond required regulatory minimums or standard practice, or (2) show innovation in meeting these minimums and standards.

## Sustainability is Context Sensitive

Because a pavement must exist and function within larger systems, practices that support sustainability must contribute to more sustainable systems and thus depend on context. As a result, a full accounting of surrounding systems and a pavement's influence on them is necessary in order to define the most appropriate sustainability practices associated with a particular pavement system.

## Importance of a Sustainability Definition

The specific definition of sustainability is considered to be of secondary importance to understanding the basic principles of sustainability; this is because a definition typically addresses what should be considered but does not give direction on how those considerations are to be prioritized or implemented. This is especially relevant because sustainability often requires the consideration of trade-offs in the decision-making process. For example, should a pavement use locally available extracted materials or make use of recycled materials that require long distance hauling? Should the benefit of a quieter surface course be selected over a pavement with a longer service life? Often, both alternatives have legitimate sustainability arguments, but the option that is ultimately selected (in other words, how sustainability is actually implemented) reflects agency, stakeholder, and project priorities and limitations. These priorities and limitations are the appropriate focal point in approaching sustainability.

### Integrating Sustainability into a System

As a system characteristic that encompasses environmental, social, and economic dimensions, sustainability is necessarily the highest-level strategy or goal of an organization. In short, sustainability tends to mean "consider everything." Other organizational strategies and goals (e.g., safety, conservation, ecosystem health, education, open space, and so on) are an expression of (1) which sustainability components an organization particularly values, (2) the order of precedence for these values, and (3) a plan to operationalize those values and precedence. This is why Amekudzi et al. (2011) and others have been able to identify many sustainability components that are already present in current transportation organization mission statements. Consequently, incorporating sustainability into an organization or into a particular system (such as pavement infrastructure) is not adding a separate value to the system but instead is assessing the current prioritization of values within that system and making changes as needed. The outcome is an alignment of the system's goals and the organization's sustainability goals. In many cases, the results of sustainability efforts are that an organization or project elevates the priorities of environmental and social issues above the levels where they were previously. However, in the strictest sense, these are only part of the overall sustainability principles discussed previously. Thus, sustainability considerations for a particular system (like pavement structures) can often be reduced to understanding how each system component affects sustainability (this is often broken down into how each component affects environmental, social, and economic outcomes) and which outcomes are most desirable given the (1) priorities of the organization, and (2) the outcomes within larger systems.

## Context: The Role of Pavements in Sustainability

While it may not be possible to quantify the "sustainability" of the planet as a whole, a few useful proxy measurements are often used as an indication of the role and relative impact of transportation and roads. As described in chapter 1, human-caused GHG emissions are often used as a simple proxy to quantify the impact of human activity on the planet. This metric can be further broken down to quantify and understand the relative contributions made by various countries, industry sectors and practices. While GHG emissions do not account for all pavement sustainability impacts, they are a useful starting point.

## Beyond Greenhouse Gas

Chapter 1 presented a brief discussion on the human-caused GHG emissions by economic sectors in the U.S. It is important to recognize that roads have sustainability impacts beyond just GHG emissions. Some of these major impacts (both positive and negative) include:

- **Energy consumption**. Roads take energy to construct, maintain, rehabilitate, and recycle. Furthermore, and often of much greater impact, roads affect the energy consumption of the vehicles using them through their interaction with those vehicles to include such properties as geometric design, surface roughness, and rolling resistance. Since the consumption of energy also tends to produce GHG, the emission of GHG is also affected by these features.
- **Habitat loss, fragmentation, and change**. Roads cause direct habitat loss over their footprint and diminish adjacent habitat, impede wildlife movement, and can change wildlife distribution in an area based on their barrier effects, roadkill, and dispersal function (Bissonette and Cramer 2008).
- **Water quality**. Pavement surfaces generally collect significant pollutants from the vehicles that use the facility, and rainwater can carry those pollutants into nearby bodies of water unless properly managed. Runoff from pavements is also often warmed, thereby affecting the temperature of streams and potentially the suitability of the habitat for some species.
- **Hydrologic cycle changes**. Pavements represent significant amounts of impervious surface and, as such, can alter the natural hydrological cycle resulting in greater stormwater runoff (and less evapotranspiration and infiltration) when compared to the same area before development.
- **Air quality**. Vehicles that use a pavement facility, as well as the equipment used to process the necessary raw materials and construct the roads, degrade overall air quality. This degradation includes not only emission from the combustion of fuel but also fine airborne particulate (less than 0.01 mm [10 micron or < PM10] in size).
- **Mobility**. Roads can contribute to a population's mobility by providing greater capacity and desirability of all transportation modes: pedestrian, bicycle, car, and transit.
- **Access**. Roads can provide greater modal access to locations. This could be vehicular access to a rural area, or it could be pedestrian, bicycle, or transit access in urban areas.
- **Freight**. Roads carry a significant amount of commercial freight across the U.S. In fact, trucking constitutes the largest share of the U.S. commercial freight industry based on value (71.3 percent) and weight (70.0 percent) (USDOT/USDOC 2010). In 2007, over $8.3 trillion worth of freight was moved via the trucking industry (USDOT/USDOC 2010).
- **Community**. Roads are long, linear forms of infrastructure exhibiting many access points and providing access and mobility. As such, they can have large community impact both positive (e.g., gathering area, sense of place, modal access, mobility) and negative (e.g., fragmentation, health issues, safety).
- **Depletion of non-renewable resources**. Roads, in their current state, require the use of a significant amount of nonrenewable natural resources (e.g., aggregate, petroleum, limestone) to construct, maintain, and rehabilitate.

- **Economic development**. Road construction and maintenance can create local employment opportunities and contribute to the ability of other businesses to function (e.g., freight transport, workers getting to/from work).

### The Role of Pavements

Within the transportation sector, GHG emissions associated with pavement construction are significant, but they are generally much less than GHG emissions associated with vehicle operations. Although there are no official statistics to quantify the magnitude of GHG emissions due solely to pavement construction, a reasonable estimate can be made using available data. First, based on a seasonally adjusted activity of $80.85 billion of highway and street construction work done in 2012 (U.S. Census Bureau 2012), and using the Economic Input-Output Life Cycle Assessment (EIO-LCA) online calculator[2] available from Carnegie Mellon University (2008), the total GHG emissions due to all highway and street construction is estimated at 117 million tons (106 million mt) $CO_2e$, or about 7 percent of the U.S. transportation total. Then, given that pavements account for about 70 percent of the highway and street construction expenditures (USDOT 2010), it can be roughly estimated that pavement construction, maintenance, and rehabilitation in the U.S. produces about 83 million tons (75 million mt) $CO_2e$ of GHG emissions, which, for comparison, is about 5 percent of the U.S. transportation GHG emission total and about 1.4 percent of the total U.S. GHG emission amount.[3] According to the EPA (2013), about 80 percent of the total emissions from the transportation sector come from cars and truck fuel combustion. Pavements also have significant potential to influence these emissions based on their design and surface characteristics largely because these can influence vehicle fuel efficiency.

This overview provides a rather crude estimate while ignoring many other important impacts, but it nonetheless gives an idea of the role of pavements in contributing to the larger GHG emissions picture. In terms of impacts beyond GHG, pavements also play a significant role but are likely secondary to roadway planning, design, and operation.

## The Pavement Life Cycle

In order to better understand the effects of pavements on sustainability, it is useful to divide a pavement's life cycle into several significant phases (see figure 2-1). This document uses the following phases:

- Materials production.
- Pavement design.
- Construction.
- Use.
- Maintenance and preservation.
- End-of-life.

[2] Using the 1997 Industry Benchmark U.S. Department of Commerce EIO dataset and selecting the "construction" industry with a "highway, street, bridge, and tunnel construction" sector.

[3] The emissions associated with pavement construction span at least three of EPA's five defined major fuel consuming sectors: electricity generation, transportation, industrial, residential, and commercial. In a strict sense, using the EPA's sector definitions pavement construction is not an exclusive subcategory of transportation.

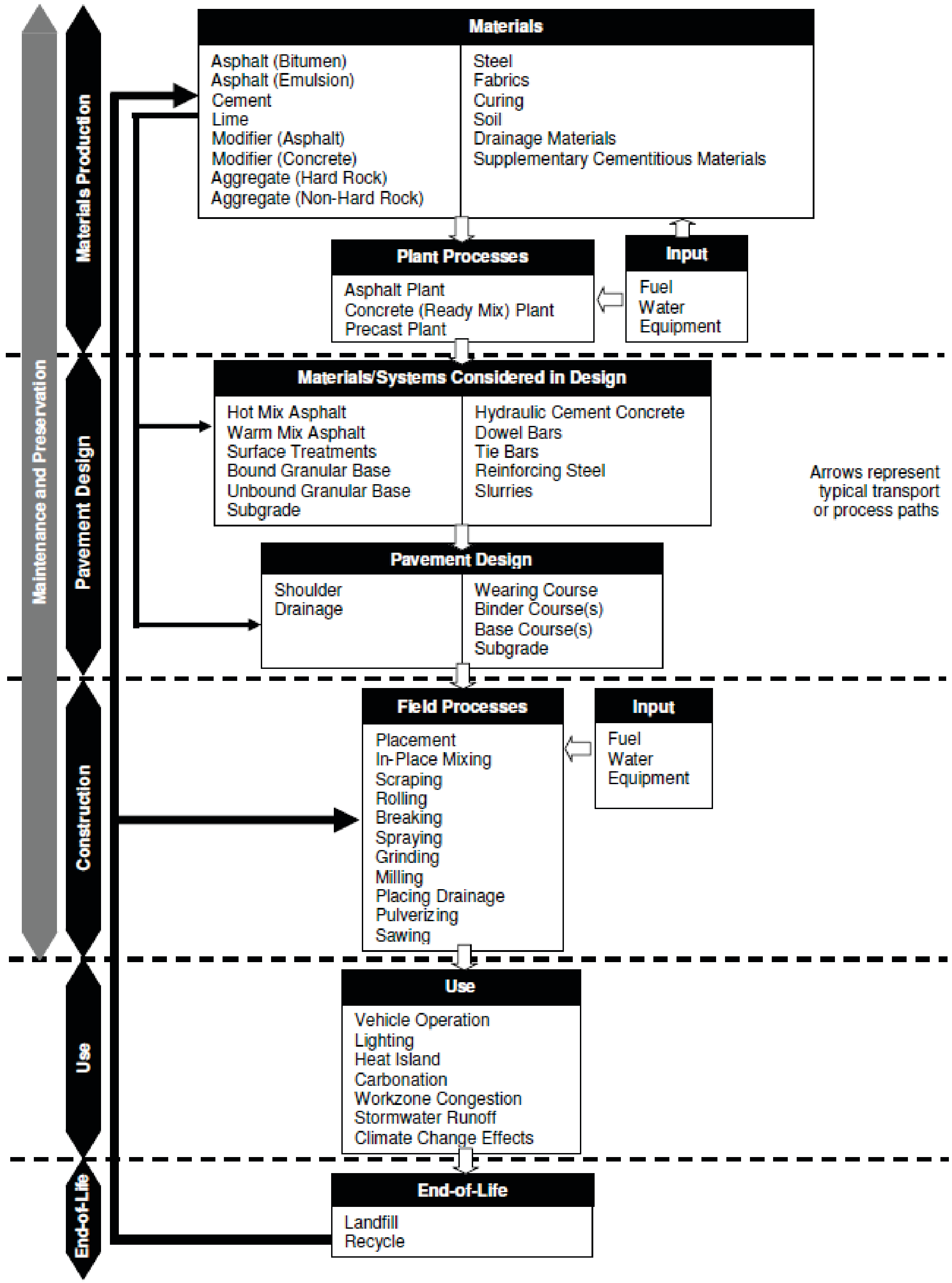


Figure 2-1. Pavement life-cycle phases (UCPRC 2010).

This section introduces each phase, how they are related, and how this document associates pavement-related processes with each of these phases. Most processes are interrelated and can conceivably be included in several different phases. However, this discussion addresses each process primarily within one particular phase. If the process is relevant to other phases, the reader is referred to the primary phase location for its discussion.

## Materials Production

Pavement materials production refers to all processes involved in pavement materials acquisition (e.g., mining, crude oil extraction) and processing (e.g., refining, manufacturing, mixing). This document includes plant processes (e.g., production of AC by mixing aggregate, asphalt cement and additives; production of concrete by mixing aggregate, cementitious materials and additives) used in the materials production phase. Materials production affects such sustainability factors as air/water quality, ecosystem health, human health and safety, depletion of non-renewable resources, and life-cycle costs. Chapter 3 addresses materials production and includes discussions on aggregates, asphalt binder, and hydraulic cements, as well as some other common construction materials used in pavement applications.

## Pavement Design

Pavement design refers to the process of identifying the structural and functional requirements of a pavement for given site conditions (subgrade, climate, existing pavement structure, traffic loadings) and then determining the pavement structural composition and accompanying materials. Included in this phase are the design processes for not only new pavement design, but also those processes associated with pavement rehabilitation (e.g., structural overlays, bonded/unbonded concrete overlays, crack-and-seat, rubblization). Structural design affects such sustainability factors as performance life, durability, life-cycle costs, construction (e.g., constructability, sequencing, schedule), and materials use. Chapter 4 addresses structural design considerations in detail for:

- **Asphalt pavements**. Asphalt pavements (constructed with AC) that may or may not incorporate underlying layers of stabilized or unstabilized granular materials on a prepared subgrade. These types of pavements are sometimes referred to as “flexible” pavements since the total pavement structure bends (or flexes) to accommodate traffic loadings.
- **Concrete pavements**. Concrete pavements (constructed with HCC) that may or may not incorporate underlying layers of stabilized or unstabilized granular materials. These types of pavements are sometimes called “rigid” pavements.

Designs that are primarily used as maintenance and preservation treatments are addressed in chapter 7, while those that are done at the end-of-life are addressed in chapter 8. Structural designs for gravel and dirt roads are outside of the scope of this document.

## Construction

Pavement construction refers to all processes and equipment associated with the construction of pavement systems. Generally, construction activities are associated with initial construction as well as subsequent maintenance and rehabilitation efforts. For the purposes of this document, construction activities are confined to actions and equipment within the project limits as well as materials transported to the project site. Production of mixtures (most notably AC and HCC) is addressed in the materials production phase. Construction activities affect such sustainability factors as air and water quality, human health and safety, durability, and work zone traffic delay, as well as project costs and time. Chapter 5 addresses construction activities in detail and includes equipment, construction sequencing, work zone traffic delay, and construction processes.

### Use

Pavement use refers to interactions with vehicle operations and the environment. A number of key pavement factors (e.g., roughness, viscoelastic energy dissipation, deflection, macrotexture) can have large effects on most sustainability metrics, including fuel economy, vehicle operating costs, and associated GHG emissions and energy use. Environmental interactions (e.g., stormwater disposition, heat capacity/conductivity, and reflectivity) can also impact other sustainability factors such as human health and safety, the urban heat island effect, and radiative forcing on a global scale. Chapter 6 addresses use factors in detail, including rolling resistance and vehicle fuel consumption, safety, noise, heat island effect, lighting, and stormwater.

### Maintenance and Preservation

Pavement maintenance and preservation refer to actions that help slow the rate of deterioration of a pavement by identifying and addressing specific pavement deficiencies that contribute to overall deterioration. This document classifies the following as maintenance and preservation: sealing, patching, seal coats, chip seals, thin overlays, in-place recycling of pavement surfaces, diamond grinding, load transfer restoration, and concrete pavement repairs. Maintenance and preservation impacts sustainability factors such as performance life, durability, life-cycle costs, construction (e.g., constructability, sequencing, schedule), and materials use. Chapter 7 addresses maintenance and preservation treatments.

### End-of-Life

Pavement end-of-life refers to the final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its useful life. This document classifies the following as end-of-life considerations: full-depth reclamation, recycled materials including reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA), and landfilling. Specific materials, designs, and construction techniques associated with end-of-life treatments are covered in other chapters, whereas the treatment and disposition of the material itself is addressed by chapter 8. End-of-life considerations impact sustainability factors such as waste generation and disposition, air and water quality, and materials use.

## Measuring Sustainability

Sustainability measurement is an evolving area of research within both the pavement and transportation fields, as it is in other areas as well (e.g., consumer products). Inconsistencies associated with definitions, system boundaries, and valuations generally make it difficult to compare the few measurement efforts that have been done to date with pavements. Currently, four general measurement tools, or methods, tend to be used either in isolation or in concert to quantify various aspects of sustainability: performance assessment, LCCA, LCA, and sustainability rating systems. Notably, there are few, if any, generally accepted metrics able to measure equity/social impacts associated with pavement systems. All the above mentioned approaches are introduced in this chapter. Chapter 10 describes in more detail the approaches and methods used for measuring and assessing pavement sustainability.

### Performance Assessment

Performance assessment involves evaluating pavement performance in relation to its intended function and specified physical attributes deemed necessary to meet that function. Metrics that provide information for performance assessment vary but include traditional condition and distress ratings (e.g., roughness, rutting, cracking, faulting), composite condition rating systems, pavement structural capacity, material design attributes (e.g., thickness, asphalt content, compressive strength, gradation), as well as mechanisms to compare these attributes to expected or design parameters. Most often, performance is addressed in relation to the current standard practice; for instance, if the current standard asphalt pavement surfacing is expected to last 15 years, the value of alternative surfacings (e.g., open-graded, stone matrix, rubber asphalt) are determined based on how their projected service life compares to the standard 15 years. While it may be a narrow view (since it does not consider added benefits), the most common sentiment is that alternatives must perform equal to or better than the current standard practice.

Because performance assessment is a longstanding method of evaluation and is essentially built into current standards, it is not addressed in detail as a measurement tool in this document. However, this document makes frequent reference to pavement performance as a critical consideration in choosing between alternatives.

### Life-Cycle Cost Analysis

LCCA is an analysis technique that uses economic analysis to evaluate the total cost of an investment option over an analysis period. As such, it is principally used to address the economic component of sustainability. The underlying assumption is that the benefits of considered alternatives are equal, and thus only costs (or differential costs) must be considered. LCCA does not address equity or environmental issues (e.g., environmental justice, clean air/water, habitat impacts) unless such issues can be monetized and treated purely as costs. Guidance for using LCCA as a decision-support tool was promulgated in the National Highway System (NHS) Designation Act of 1995 for large NHS projects (those greater than $25 million) but later rescinded in the 1998 Transportation Equity Act for the 21st Century (TEA-21) (Walls and Smith 1998) based on a perceived lack of guidance. Nevertheless, many government documents and agencies recognize the utility of LCCA and related financial analyses (e.g., Executive Order 13123, OMB Circular No. A-94) and most highway agencies practice LCCA (largely guided by Walls and Smith, 1998) to some degree in selecting pavement type for major projects (Rangaraju, Amirkhanian, and Guven 2008). The most prevalent LCCA software tool is the FHWA's *RealCost* program (FHWA 2011).

### Life-Cycle Assessment

LCA is a technique that can be used for analyzing and quantifying the environmental impacts of a product, system, or process. The International Organization for Standardization (ISO 2006) states that LCA is a process that "addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition, through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle to grave)."

LCA is a field of science that is still very much evolving, yet it has demonstrated real-world value over the last two decades by helping manufacturers, companies, governments, and other groups identify what is environmentally important to them and then to define needed action to lower those environmental impacts. It is widely used for material profiling and is increasingly being looked at for use in a number of applications, one of them being pavements. LCA is very powerful in that it relates environmental impacts to the overall performance of a system (such as a pavement) over the lifespan of the application and over a wide set of environmental performance indicators. This systematic approach identifies where the most relevant impacts occur and where the most relevant improvements can be made while identifying potential trade-offs to other life-cycle phases or impact categories.

### Rating Systems

A sustainability rating system is essentially a list of sustainability best practices with an associated common metric. This metric, usually expressed in terms of 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 using a common unit (points). 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 systems available in the transportation community.

### Integrating Measurement Systems

The previously discussed methods can be used alone or in concert to measure sustainability. Using them in concert provides a more holistic assessment of sustainability since each system tends to either address one specific component of sustainability in detail or address all components in less detail. For instance, performance assessment can provide a quantitative assessment of fitness for use, but does not address cost or environmental impact. LCCA and LCA could supplement a performance assessment by providing quantitative assessments of cost and environmental impact. Using performance assessment, LCCA, and LCA in concert can provide a good, yet still incomplete, picture of the overall sustainability impact of a pavement system. It is incomplete because (1) there are no common existing systems that provide quantitative assessments of social issues associated with pavements, and (2) it can be unclear how to relate the values obtained from performance assessment, LCCA, and LCA (i.e., which is most important and to what degree?). Rating systems can address these issues to some extent in that they attempt to incorporate all components of sustainability and usually relate them to one another using a common point system. However, in order to do this, they tend to sacrifice detail, and the inclusion/exclusion of sustainability best practices and their relative weighting within a rating system is somewhat subjective.

Ultimately, the sustainability measurement systems used depend upon the priorities and limitations of the agency and the characteristics of the project, as well as the desired outcomes viewed within the context of larger systems. For instance, a statewide GHG reduction goal lends itself to using 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 favor the use of a rating system that takes a broad view of sustainability. Furthermore, it is also possible to target certain credits within a rating system for accomplishment based on agency or project goals (Muench, Armstrong, Allen 2012). In other words, rather than creating a new rating system from scratch to be used as an internal performance metric, an agency could use an existing one and target those credits that are consistent with its strategic sustainability goals.

## Reasons to Measure Sustainability

The reasons to measure sustainability can be placed in three broad categories: accounting, decision support, and process improvement. Each of these is described in more detail below.

### *Accounting*

"Accounting" refers to measurement for the sole purpose of quantifying. Usually this is in response to a reporting requirement, most often associated with GHG reporting and reduction limits. While initial cost has long been measured, there are currently no broad regulations within the U.S. to quantify sustainability. In Europe, quantification is more advanced with some owners requiring GHG or energy assessments, even for competing alternatives considered in design. In the U.S., it is likely that any future initiatives or mandates involving GHG emissions inventories will require measurement of GHG emissions at the national, state, agency, or project level. These initiatives/mandates can be broadly classified as:

- **National Environmental Policy Act (NEPA) requirements for large GHG emitters**. The draft guidance from the Council on Environmental Quality (CEQ) states: "…if a proposed action would be reasonably anticipated to cause direct emissions of 27,500 tons (25,000 mt) or more of $CO_2e$ GHG emissions on an annual basis, agencies should consider this an indicator that a quantitative and qualitative assessment may be meaningful to decision makers and the public" (Sutley 2010). Generally, 27,500 tons (25,000 mt) is beyond what even a large paving project would generate. However, paving may play a smaller role in projects that meet or exceed the 27,500 tons (25,000 mt) criterion (Sutley 2010).
- **State GHG reduction mandates and reporting registries**. At least thirty states have some sort of official GHG reduction mandate, while forty-two have some form of reporting registry (i.e., they report GHG totals but not all are mandated to reduce them) (Center for Climate and Energy Solutions 2012). As state governments continue to flesh out these mandates and reporting requirements, they will have to take inventory of their GHG emissions at some level. While this may not initially involve pavements, their eventual inclusion cannot be discounted.
- **Cap-and-trade**. Various cap-and-trade initiatives are predicated on the ability to inventory GHG emissions. While a federal cap-and-trade program is not likely to be implemented in the near future, many agencies have entered into various cap-and-trade programs including the Western Climate Initiative (WCI), the Midwest Greenhouse Gas Reduction Accord (MGGRA), and Regional Greenhouse Gas Initiative (RGGI).

In general, these initiatives are at a high level, and it remains to be seen how their requirements will be interpreted to apply to pavement systems and the traffic which they support.

### *Decision Support*

"Decision support" refers to measurement done to obtain quantities or qualities that can help in making organizational or project decisions. Results of multiple alternatives are often compared but may not be used to improve individual alternatives or processes. Decision-support tools can be mandated (e.g., many states require LCCA for pavement projects above a certain size) but many are not. Based on the language of the current U.S. transportation bill (Senate and House of

Representatives 2012), the use of LCCA may become even more prominent in the future. Pavement management systems (PMS) are an example of a decision-support tool that most states and large owner agencies possess. They measure pavement condition and track new construction, rehabilitation, preservation, and (in some cases) maintenance actions in an effort to identify appropriate rehabilitation/preservation/maintenance treatments and their timing in order to optimize pavement network condition. Decision support using LCA and sustainability rating systems is in its infancy in the U.S. transportation industry; there are a few systems publically available but their current use is, generally, experimental. However, it should be noted that the use of LCA (and its predecessors) for decision support in other industries has a history dating back to at least the 1960s.

#### *Process Improvement*

"Process improvement" refers to measurements that provide feedback data in support of refining and updating the overall methodology. Measurements can be compared to benchmarks or other indicators and then processes can be altered or modified to produce better results. Process improvement is one of the stated purposes of the FHWA's *Infrastructure Voluntary Evaluation Sustainability Tool* (INVEST) sustainability self-assessment tool (FHWA 2012) and the New York State DOT's *Green Leadership in Transportation Environmental Sustainability* (GreenLITES) program (NYSDOT 2012). Currently, process improvement as it relates to sustainability is not mandated and the use of measurement tools is minimal, but such use may be increasing.

### Trade-off Considerations

Since sustainability is a broad systems characteristic encompassing virtually every impact a system has, most pavement features and qualities can be argued to support sustainability goals in one way or another. However, it is unlikely that all such features can be included in a pavement, either because some features support one sustainability objective but are in opposition to another, or because some features are mutually exclusive. For instance, an open-graded friction course (OGFC) may be desirable because it reduces tire-pavement noise and provides health benefits to the surrounding area (supports the social/equity component), but the same surface may also have a much shorter performance life (especially in the presence of studded tire wear), which would make its life-cycle cost substantially higher than a more traditional dense-graded AC surface (in opposition to the financial portion of the economy component). As another example, it may be desired to incorporate recycled materials in a rural paving project, but the nearest source of recycled material is 100 mi (161 km) away while an acceptable local extracted material is only 5 mi (8 km) away. In these instances, it is necessary to analyze the available options within the context of sustainability in order to make the best choice.

Essentially, this choice between multiple alternatives represents a consideration of "opportunity cost," the cost of an alternative that must be foregone in order to pursue a certain action (Investopedia 2012). In the previous example, if the local extracted material is selected in favor of the non-local recycled material, the difference in value between the two represents an opportunity cost. The difficulty is in determining the value of the alternatives in a sustainability context. In classic economics, value is usually expressed in monetary units (i.e., dollars). However, value in a sustainability context can have many different metrics expressed in many different units, some of which may be controversial or difficult to quantify. Some examples of sustainability value include life-cycle cost, GHG emissions, energy use, water/air quality, waste generation, scenic views quality, art, community context, history, habitat continuity, and performance life. Historically, the value of alternative pavement features has been overwhelmingly based on economics, often being based on initial construction cost alone. While important, initial cost represents an incomplete view of the overall costs and benefits of a particular feature. Even standard LCCA procedures tend to ignore benefits and costs that are not easily monetized.

Ultimately, this consideration of trade-offs is essentially a benefit/cost analysis done in a more holistic sense (i.e., considering more than just economics). This section describes considerations when contemplating trade-offs for pavement sustainability best practices. Or, put differently, this section describes a few key items to be considered when conducting a benefit/cost analysis of sustainable pavement features. Even if benefits and costs are difficult to quantify, it is important to use a consistent approach in analyzing trade-offs to avoid introducing unintended bias. In general, these considerations involve the following: priorities and values of the organization or project, performance, cost, impact magnitude and duration, and risk. None of these considerations is new, so this section amounts to a formal articulation of what they are. These basic trade-off considerations are referenced throughout this document.

### Priorities and Values of the Organization or Project

Since sustainability is such a broad system concept, most pavement features support some component goals and may be in opposition to others. Thus, judgment on the sustainability value of a pavement feature depends on the relative value of sustainability components. Therefore, organization or project goals and priorities should be considered in evaluating trade-offs. Ideally these goals and priorities should indicate (1) which sustainability components an organization or project particularly values, (2) an order of precedence for these values, and (3) a plan to operationalize those values and precedence. If sustainability goals and priorities exist and are clearly articulated, the first order trade-off consideration is to favor the feature that best supports those values.

In some cases, LCA can be used to quantify and compare environmental impacts, while in other cases quantification is difficult, if not impossible. In these cases, it may be enough to determine the general duration of impact (that is, does it occur just during construction or is it over the entire life of the pavement) in order to make a decision.

### Risk

All pavement sustainability choices involve an amount of risk. Generally, "risk" means that there is some uncertainty regarding the impact and cost of a selected alternative and such uncertainty leaves open the possibility of less desirable outcomes than predicted on average. For instance, a composite pavement may be selected as the preferred alternative because it results in the lowest life-cycle cost among alternatives considered. However, if inadequate bonding is developed between the surface and underlying layers, it may be that performance life is substantially reduced, resulting in a much higher life-cycle cost. Metrics that provide a probabilistic-based analysis (e.g., *RealCost* [FHWA 2011], *Construction Analysis for Pavement Rehabilitation Strategies—CA4PRS* [Caltrans 2008]) can help quantify risk due to uncertainty. Some metrics, like LCA, are only now beginning to incorporate uncertainty into their analysis.

## Summary

This chapter provides a general overview of sustainability concepts and describes how they relate to pavements. This includes a basic definition of sustainability and a discussion of why sustainability essentially means "consider everything," yet also explains how its application must fall within the priorities and goals established by the organization. The role that pavements play in sustainability is described in terms of a common proxy (GHG emissions), and the key components of the pavement life cycle (materials production, pavement design, construction, use, maintenance and rehabilitation, and end-of-life) are also presented. The chapter concludes with summary of current methods for assessing sustainability and a general framework for considering potential issues and trade-offs.

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