EXECUTIVE SUMMARY

This document has been prepared to provide guidance to the pavement community on sustainability considerations in pavement systems, drawing from and synthesizing the large and diverse body of technical information that exists on the subject. Sustainability considerations throughout the entire pavement life cycle are examined (from material extraction and processing through the design, construction, use, maintenance/rehabilitation, and end-of-life phases) and the importance of recognizing context sensitivity and assessing trade-offs in developing sustainable solutions are emphasized. Key points from each of the eleven chapters contained in the document are summarized in the following sections.

Chapter 1. Introduction

Chapter 1 provides a broad introduction to sustainability and its importance in pavement engineering. It also describes the overall scope and target audience for the document.

- **What is sustainability?** Most definitions of sustainability begin with that issued by the World Commission on Environment and Development (WCED, often referred to as the Brundtland Commission) in 1987: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Moreover, sustainability is often described as a quality that reflects the balance of three primary components: economic, environmental, and social impacts, which are often collectively referred to as the “triple-bottom line.” A focus on sustainability can be interpreted as a recognition of the importance of all three triple-bottom line components. However, the relative importance and consideration of each of these factors are context sensitive and very much driven by the goals, demands, characteristics, location, materials, and constraints of a given project, as well as the overarching goals of the sponsoring agency.
- **Systems approach to sustainability**. In this context, more sustainable pavement systems are achieved through the balanced consideration of a number of trade-offs and competing priorities for a given project. It is important to recognize that, in some cases, it may not be productive (and it may even be counterproductive) to introduce certain features that are thought to be sustainable. For example, the use of recycled materials may not improve project sustainability when the economic and environmental costs of transporting the material over a great distance outweigh the benefits of using that material. This is the type of trade-off that must be continually assessed as the pavement industry moves towards more sustainable solutions.
- **Scope of the document**. This document focuses exclusively on the sustainability considerations associated with the pavement structure and pavement materials, and only those pavements constructed with a semi-permanent surface.
- **Target audience**. The primary audience for this document are practitioners doing work within and for state Departments of Transportation (DOTs), and it is intended for designers, maintenance, material and construction engineers, inspectors, and planners who are responsible for the design, construction, and preservation of the nation’s highway network.

Chapter 2. Concepts of Pavement Sustainability

This chapter presents the basic concepts of pavement sustainability, and includes definitions, an overview of the pavement life cycle, an outline of sustainability issues and trade-offs, and an overview of how sustainability can be measured.

- **Sustainable pavements defined**. "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.
- **Sustainability is an aspirational goal**. It is unlikely a truly "sustainable" pavement will be constructed in the near future so pursuit of sustainability should be viewed as a process of continual improvement towards an ultimate goal. This document, therefore, highlights "sustainability best practices," which are processes, actions, and features that advance the state of the practice towards more sustainable pavements.
- **Sustainability is context sensitive**. There needs to be a full accounting of surrounding systems and a pavement's influence on them in order to define the most appropriate sustainability practices associated with a particular pavement system. Furthermore, the approach must be tailored to fit into the overall goals and objectives of the agency.
- **Pavement sustainability includes a large range of issues**. Among other items, this can include such things as greenhouse gas (GHG) emissions, energy consumption, impacts on habitat, water quality, changes in the hydrologic cycle, air quality, mobility, access, freight, community, depletion of non-renewable resources, and economic development. Again, these must be considered within the confines of the particular project and the goals of the agency.
- **Sustainability measurement is an evolving field**. The "measurement" of sustainability is the first step in being able to establish benchmarks and assess progress. Currently, four general measurement tools, or methods, can be used to quantify sustainability: performance assessment, life-cycle cost analysis (LCCA), life-cycle assessment (LCA), and sustainability rating systems. These 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. Considerable work remains on establishing the framework and boundaries for pavement LCA, and outside of some treatment by rating systems, metrics to measure equity/social impacts associated with pavement systems do not currently exist.
- **Considerations of trade-offs is important**. The considerations of trade-offs is essentially a benefit/cost analysis performed in a more holistic sense (i.e., considering more than just economics). 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 should include the priorities and values of the organization or project, costs, impact magnitude and duration, and risk.

Chapter 3. Materials Considerations to Improve Pavement Sustainability

Chapter 3 reviews the materials commonly used in paving applications—including aggregate, asphalt, and cementitious materials—and describes how the production and use of those materials affect the overall sustainability of the pavement system. The scope is from the production or manufacture of materials to the point where the materials arrive at the construction site, either on grade or before leaving the plant. Sustainability impacts of other materials commonly used in pavements (such as steel, reinforcing fibers, interlocking concrete pavers, soil modifiers and stabilizers, and geosynthetics) are also discussed.

- **Consideration of life-cycle impacts of materials is important**. Impacts from material acquisition through processing, construction, use, and ultimately to the end of life need to be considered. Discussions are presented concerning the decision-making process inherent in material selection, the use of recycled, co-product, and waste materials (RCWMs), overall constructability considerations, trade-offs between higher quality materials and transportation costs/impacts, and the unintended consequences of restrictive specifications.
- **Sustainability impacts of aggregates**. Specific strategies are presented to improve the sustainability of aggregate production. In general, reducing the use of virgin materials and increasing the use of locally available materials and the use of durable RCWMs improves overall sustainability. Future challenges include more widespread use of RCWMs as aggregate, the ability to successfully incorporate "marginal" aggregates into pavement systems, and more sustainable transportation of aggregate over greater distances.
- **Sustainability impacts of asphalt materials**. Asphalt-based materials have evolved significantly in recent years, with increased amounts of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) being used to replace virgin binder. Moreover, increased levels of polymerization and the addition of rubber are being used to develop binders that are better suited to modern paving and preservation needs, to create specialized mixtures to provide improved structural support, and to enhance safety and reduce noise. Multiple approaches for improving sustainability with regards to asphalt materials are presented, including reducing virgin binder and virgin aggregate content in hot-mix asphalt (HMA) and warm-mix asphalt (WMA) mixtures, reducing energy consumed and emissions generated in mixture production, use of alternative binders, extending the life of asphalt mixtures, reducing materials transportation impacts, extending lives of seal coats, reducing the need for new materials, and increasing surface reflectivity (where warranted).
- **Sustainability impacts of concrete materials**. The major challenge facing cementitious materials is that the production of the primary binder (portland cement), is energy- and GHG-emission intensive. Reductions in those energy and emission levels is best met by expanding efforts to reduce the amount of portland cement used in paving mixtures. Several strategies are presented to achieve this, including the use of improved aggregate gradations, the use of portland limestone and blended cements, and the increased use of supplementary cementitious materials (SCMs) added at the concrete plant. Other approaches for improving the sustainability of concrete materials includes reducing water use in concrete production, increasing the use of RCWMs and marginal aggregates, and improving the durability of paving concrete.

Chapter 4. Pavement and Rehabilitation Design to Improve Sustainability

This chapter describes sustainability considerations through the design process for both asphalt and concrete pavements. The focus is on new pavement design and structural rehabilitation, including reconstruction and structural overlays. Pavement design considerations are described, as is the concept of "payback time," which is useful when evaluating the sustainability of design approaches that incur a larger initial economic or environmental impact as compared to standard practices.

- **Improved pavement design procedures.** Mechanistic-empirical pavement design procedures offer the promise of more efficient pavement designs for the prevailing traffic, climatic, and locational design conditions, which contributes to the overall sustainability of the resultant design.
- **Optimized use of materials**. Innovative pavement designs that incorporate the optimized use of materials and cross sections are an attractive means of meeting performance requirements while achieving environmental and economic benefits.
- **Evaluation of pavement designs**. Pavement designs can be evaluated by using LCA, LCCA, and rating systems to assess their environmental and societal impacts so that they can be improved. Moreover, several key use-phase issues, such as smoothness, noise, and stormwater management, can be considered in the design stage to help control later use-phase impacts.
- **Sample design strategies**. Some sample design strategies that may address sustainability issues for given projects are described, including long-life asphalt and concrete pavements, use of inlays, structural designs using local materials/low-impact transportation, accelerated construction, noise-reducing surfaces, modular pavement systems (including concrete pavers), pavement strategies for stormwater management, and consideration of use-phase impacts in the design phase.
- **Emerging trends in pavement design**. Among the emerging trends in the pavement design area are ongoing improvement to mechanistic-empirical pavement design procedures, the integration of design and environmental impact analyses, the consideration of emerging materials and future maintenance and rehabilitation in design, the possible integration of performance-related specifications, and improved smoothness prediction models.

Chapter 5. Construction Considerations to Improve Pavement Sustainability

This chapter briefly reviews the key elements to be considered to enhance the sustainability of construction for both asphalt and concrete pavements. This includes discussions on specifications, construction setup and operations, reduction of construction equipment fuel and emissions, management and handling of construction materials, construction quality assurance, and effective lane closures.

- **Pavement construction affects sustainability**. Pavement construction has an effect on the overall sustainability of a project. For example, construction-related fuel consumption, exhaust emissions, particulate generation, noise generation, and traffic delays and congestion are typical construction-related impacts. Furthermore, the area surrounding the construction site is also impacted by the pavement construction due to possible effects on residents, businesses, and local ecosystems.

- **Improving sustainability of pavement construction operations**. Sustainability improvements in the pavement construction process can be gained through the optimization of construction planning and sequencing, the control of erosion and sedimentation, the management of construction-related traffic delays, the control of on-site equipment- and construction-related noise, and the management of construction waste. At the same time, regulations continue to require improvements in the operation efficiency of construction equipment, lowering combustion emissions such as VOC and NO_x, diesel particulates, and fugitive particulate matter. Quality assurance is an essential element in constructing a durable pavement and, consequently, is essential in improving the overall sustainability.
- **Emerging technologies and construction techniques**. A number of innovative technologies are being adopted to improve construction efficiency, quality, and monitoring, including techniques such as intelligent compaction, stringless paving, infrared thermographic scanning, and real-time smoothness measurement. At the same time, new construction techniques, such as two-lift concrete paving and the use of cold plant asphalt mixes, have the potential to revolutionize construction, minimizing the use of non-renewable virgin materials and maximizing the use of RCWMs.

Chapter 6. Use-Phase Considerations

Chapter 6 identifies the critical sustainability impacts associated with pavement structures while they are in service, commonly referred to as the use phase. This chapter includes discussions of rolling resistance and fuel consumption, tire-pavement noise, stormwater management, pavement thermal performance, lighting, and safety, all of which, in turn, can also affect water quality, air quality, and, ultimately, human health.

- **Achieving and maintaining smoothness**. Achieving the highest level of smoothness during initial construction and maintaining that level throughout the service life is a key factor in improving fuel economy and reducing vehicle emissions, especially for heavily trafficked pavements.
- **Utility cuts.** In urban areas, pavement roughness is often affected by the quantity of utility cuts and the quality of the repairs. The smoothness of pavements in locations where there are utilities should be preserved by avoiding utility cuts where possible, and by obtaining the best possible repairs to cuts where they must be performed. An alternative for new pavement construction is to place utilities in locations on the right of way outside of heavily trafficked portions of the paved areas.
- **Structural responsiveness and vehicle fuel economy.** Several mathematical models have been developed and a number of field studies have been performed to assess fuel economy on different pavement structures. These provide indications that under various conditions the structural responsiveness of different pavements to vehicle loading can have a measureable effect. However, unlike roughness, this effect is highly dependent on pavement temperatures and is much more sensitive to vehicle type and speed. The calibration of models that will allow definitive conclusions to be drawn based on general application of the models to a wide range of pavements under a broad range of traffic and climatic conditions in various locations has not yet been completed.
- **Noise emissions**. Although other factors are typically more important than the pavement in determining noise levels, noise attributable to the pavement surface characteristics can

be detrimental to surrounding communities and habitat. Tire-pavement noise emissions can be partly addressed through the selection of appropriate paving materials and/or surface textures.

- **Stormwater management**. Permeable pavements are an effective means of providing stormwater management by capturing and storing runoff, reducing contaminants in waterways, and recharging groundwater supplies. They also make for more efficient land use by eliminating the need for retention ponds and swales. These pavements are currently limited to low-volume roadways and parking lots.
- **Urban Heat Island Effect (UHIE)**. Relationships between the pavement surface reflectivity and the UHIE are very complex; influencing factors include such items as the size of urban area, the pavement density, solar reflectance, tree canopy, building patterns, and the climate. In certain cases, surface reflectivity may be significant and thus should be evaluated within the specific context of a given project. At this time, it is unclear to what degree pavement solar reflectance impacts the development of the UHIE for different urban architectures, climate regions, and other variables. Research is underway to provide a more comprehensive understanding of the UHI phenomenon.
- **Lighting.** The high energy demand of current lighting systems has a significant economic and environmental footprint. Pavement surface luminance is known to influence the amount of artificial lighting required, but practical application of this knowledge is currently unclear as surface luminance changes with time. Development and implementation of new adaptive lighting systems, which provide lighting only when it is needed, is currently underway and has the strong potential to significantly lower economic, environmental, and societal costs associated with artificial lighting.
- **Safety**. Pavement characteristics that impact safety include smoothness, friction, cross slopes, porosity, and constructed features such as rumble strips. Smoother pavements provide a comfortable riding surface and cause less distractions for the driver, high friction levels are especially important in specific cases such as ramps and curves, adequate cross slope is required to promote surface drainage and prevent hydroplaning, porous pavements minimize splash and spray (thereby improving visibility in wet weather conditions), and rumble strips alert drivers of changing conditions.

Chapter 7. Maintenance and Preservation Treatments to Improve Sustainability

This chapter presents the maintenance and preservation treatments most commonly used on asphalt and concrete pavements. Currently there is limited information available on quantifying the sustainability of pavement maintenance and preservation practices, so much of the current analysis is subjective. Still, opportunities exist for enhancing pavement system sustainability through careful treatment selection, materials considerations, treatment timing and application, and treatment design and construction.

- **Linking pavement management systems and pavement preservation**. The need for the further integration of various asset management systems and overall pavement sustainability considerations is stressed, including the consideration of environmental factors in the analysis of pavement performance.
- **Effect of traffic volumes**. On higher traffic routes, the higher economic cost of more frequent treatments (including lane closures/traffic disruptions) may be offset by large reductions in environmental impacts due to vehicle operations on smoother pavements.

For lower traffic routes, the minimization of agency life-cycle cost through proper timing of the right treatment also generally improves sustainability.

- **Treatment selection factors**. Critical factors for consideration in selecting a suitable maintenance or preservation treatment includes performance history of the treatments, overall performance needs or requirements, construction constraints, LCCA, and LCA.
- **Favorable factors for sustainable treatments**. The sustainability value of any given treatment is difficult to judge as there are multiple factors at work; however, in general, treatments that use the least amount of material to maintain smoothness over the longest period of time have the greatest positive effect. Moreover, understanding the complete life-cycle impacts is an essential element in establishing the advantages and disadvantages of any given treatment. Unfortunately, available data are currently insufficient to support detailed environmental analyses to characterize maintenance and preservation treatments.

Chapter 8. End-of-Life Considerations

Chapter 8 discusses the impacts of the end-of-life phase on the sustainability of both asphalt and concrete pavements. Critical end-of-life issues and strategies for improving pavement system sustainability are presented.

- **Increase use of RCWMs**. These materials can be incorporated in virtually every layer of the pavement structure and are effective means of increasing the sustainability of pavements. Recycling processes can be conducted off site (e.g., in central plants) or on site, using various technologies.
- **"Highest use" of recycled materials**. The "highest use" refers to the preferred use of a recycled material in order to extract the greatest payback in terms of sustainability. This requires the consideration of all of the costs involved in recycling and using a particular material. Under such an approach, a material such as RAP, for example, would find its highest use as a replacement for both binder and aggregate in a new asphalt mixture instead of being used as an aggregate base. This approach also considers the costs of transporting materials and landfilling to ensure that materials are employed according to their highest value.
- **Specific end-of-life strategies**. Multiple end-of-life strategies are discussed for both asphalt and concrete pavements, including central plant recycling and full-depth reclamation for asphalt pavements and the use of recycled concrete as base material or as aggregate in new concrete or asphalt. The specific incorporation of these strategies on a given project is based on the project needs, context sensitivity, and agency goals. Landfilling as an end-of-use option is becoming less attractive because of dwindling landfill space and the value associated with recycling and reusing pavement demolition products.

Chapter 9. Pavement Sustainability within Larger Systems

This chapter presents various sustainability considerations that are not addressed elsewhere in the manual. These impacts can influence decisions even though they are often not easily quantifiable.

- **Systems approach required**. When evaluating and incorporating other aspects, an overall "systems" approach is required to consider the entire reach and totality of the pavement and roadway setup.
- **Role of pavements**. The role of pavements in a larger system is discussed in terms of aesthetics, historical and cultural identity, the impact of utility cuts, and the impact of odor, soot, and particulate matter. An example of aesthetics impacting pavement design is documented along State Road 9 in Utah, in which a chip seal surfacing that uses local red volcanic cinders was placed to ensure that the pavement surface matched the aesthetics of the surroundings.
- **Emerging technologies**. A number of technologies are emerging in this area, with examples including the use of photocatalytic pavement, the ongoing evolution of modular pavement systems, and the development of pavements that produce energy.

Chapter 10. Assessing Pavement Sustainability

This chapter provides information on measuring pavement sustainability and why it is important. An overview of sustainability rating systems is provided, along with a summary of LCCA and LCA procedures.

- **Need for measuring sustainability**. In order to move forward with sustainability considerations in pavements, it is important that there be ways to measure it so that baseline levels can be established and future progress can be assessed. Together, LCCA, LCA, and sustainability rating systems provide a means of quantifying economic, environmental, and societal factors in pavement sustainability.
- **LCCA**. LCCA is a widely accepted technique for evaluating the economic impacts of pavement systems. At its very core, it 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. The most widely accepted and adopted LCCA tool for pavement applications in the U.S. is the FHWA's *RealCost* Software.
- **LCA**. LCA is an emerging technology that works to quantify environmental impacts over the entire life cycle of the pavement system; results are expressed, in terms of a number of key environmental factors (commonly energy usage and greenhouse gas emissions, but there are many others). Pavement-specific LCA tools are not available yet, but several software programs can be used with customization to assess pavement environmental impacts.
- **Sustainability rating systems**. A sustainability rating system is essentially a list of sustainability best practices with an associated common metric (commonly expressed as "points"). 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). A number of rating systems relevant to pavements are described (e.g., Greenroads®, INVEST, Envision™, GreenLITES).
- **Integration of assessment methods**. LCA, LCCA, and rating systems 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.

Chapter 11. Concluding Remarks

This chapter summarizes several of the technologies and innovations that are contributing to sustainability initiatives along with recommended implementation activities for helping to move the process forward.

- **Technologies and innovations**. A number of technologies and innovations are being used to improve pavement sustainability, including, among others, the increased use of recycled materials, adoption of WMA technologies as a standard practice, reduction of portland cement and increased use of SCMs and RCWMs in concrete, optimization of materials and cross sections, and the expanded use of preservation treatments.
- **Sustainability trends**. Several trends emerging in the area of pavement sustainability include a growing understanding of the importance of the use phase, a recognition that pavement systems are a small part of much larger systems, and the development/enhancement of sustainability tools.
- **Sustainability is context sensitive**. Sustainability is very much context sensitive, and that sustainable strategies will depend on the characteristics of the project, the materials and technologies that are readily available, and the specific economic, environmental, and societal goals of the agency.
- **Implementation of sustainability**. Key factors essential to the implementation of sustainability considerations within the pavement community include leadership at the national and state levels, partnerships between key stakeholders, effective education and outreach, identification of knowledge gaps, development of focused research strategies, and the development and application of useful LCA tools.