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# Chapter 13 - Sustainable Pavement Management

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## Introduction

Sustainable pavement management is an emerging field within infrastructure management that is concerned with maintaining acceptable condition of pavements while also considering the tradeoff between cost, environmental impacts and social impacts of pavement investments. Generally the tradeoff between economic, environmental and social factors requires that the agency in charge of managing pavements maintains an accurate database that includes the pavement condition and models to predict the resulting impacts of pavement management decisions on each of the factors. In many cases, assumptions must be made about the environmental and social impacts, and therefore pavement management decisions must reflect the level of certainty that the agency has in the assumptions. Consequently, a high level of uncertainty in many cases tends to lead the agency to only consider economic considerations within pavement management, and environmental mitigation techniques are employed after the selection of the intervention or design of the pavement is complete.

## Sustainable Infrastructure

Infrastructure can be seen as the foundation that connects the natural environment to the economy and social systems by facilitating the movement of goods, services, and people. The consequence of this connection is that the quality of infrastructure has a direct impact on the economy, the quality of the natural environment and the quality and equity of societies. This is what is generally known as the triple bottom line of sustainability (balancing economic, environmental and societal impacts). In light of this, sustainable infrastructure can be viewed as infrastructure that maximizes the quality of life of a society and economic benefits while also minimizing detrimental impacts on the natural environment.

The American Society of Civil Engineers (ASCE) has defined sustainability as; "A set of environmental, economic and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely without degrading the quantity, quality or the availability of natural, economic and social resources" (ASCE, 2012). Thus, to promote a truly sustainable transportation network, decisions made about the treatment and expansion of the network should take into account environmental and social factors, along with economic and technical considerations. In order to implement sustainability into civil infrastructure, ASCE has applied the definition of sustainability to sustainable development as, "the process of converting natural resources into products and services that are more profitable, productive, and useful, while maintaining or enhancing the quantity, quality, availability and productivity of the remaining natural resource base and the ecological systems on which they depend" (ASCE, 2012).

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## Pavement Management

Sustainable pavement management is the application of sustainability considerations to traditional pavement management practices. Thus, an understanding of pavement management principles is essential to understanding how to management pavement assets more sustainably. It is well known that maintaining pavements by merely rehabilitating pavements that are in the worst condition is not an economically optimal strategy (Hudson, et al., 1997). Instead, a balance must be made between rehabilitating pavements in poor condition and preserving pavements in good condition, often in the face of limited funding. Finding the optimal maintenance and rehabilitation (M&R) strategy given several pavement assets in varying conditions and several M&R options is the foundation of pavement management. More formally, pavement management is a systematic, objective, and consistent procedure to assess the current condition and predict future condition of pavements given certain constraints (e.g. budgetary) and M&R options (Shahin, 2005). This follows the terminology provided by Hudson et al. (1997), which defined management as, "the coordination and judicious use of means and tools, such as funding and economic analysis to optimize output or accomplish a goal of infrastructure operation".

## Level of Decisions Supported

Pavement management includes analysis at multiple levels, generally divided into the strategic level, network level and project level (Flintsch & Chen, 2004). Figure x.1 illustrates the relationship between these decision levels, extent of the network involved, and detail of data required for supporting these decisions. The strategic level is where broad goals and objectives are set for the various transportation assets, including the pavement network, and budgets are determined and allocated to different goals and modes. This may include such broad statements as, '*Maintain the pavement in good condition*', or '*Increase safety for the travelling public'*. The next level of pavement management in terms of increasing detail is the network level. The network level is where the pavement budget is defined, and candidate projects are selected based on a needs analysis. The data used in network level analysis is considerably less detailed than the data required for a pavement design, and is generally represented by broad indicators (e.g. the Pavement Condition Index as defined by ASTM International (ASTM International, 2011)). Following the project selection step, each project selected at the network level is investigated at a higher level of detail, also known as the project level. Project level data is detailed enough to use for specific pavement designs.

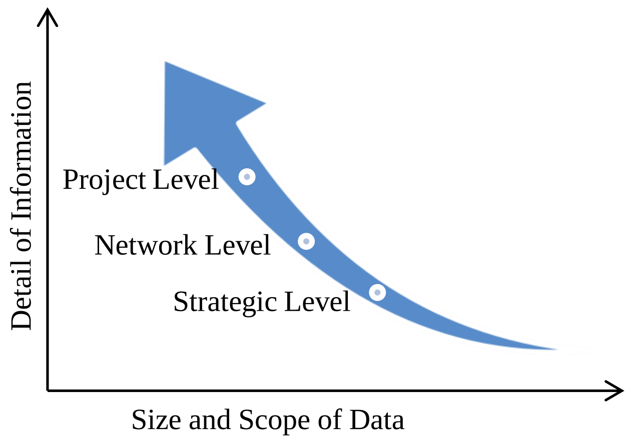


**Figure x.1 Levels of Decisions in Pavement Management**

## Pavement management as a key asset management business process

Pavement management falls under the umbrella of asset management, where the pavements are viewed as assets that have inherent values, expected life's and risks.  Asset management is a process by which an agency attempts to make optimal decisions about resource allocation and future planning based on a number of engineering, economic and social issues. The American Association of State Highway Transportation Officials (AASHTO) defines asset management as the following (Cambridge Systematics, Inc., 2002);

> "a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle, focusing on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well defined objectives."

It is widely recognized that asset management requires cooperation throughout the entire agency. Thus, asset management should involve processes by which an agency involves its employees in improving organizational effectiveness in the accomplishment of agency mission and goals. This requires the establishment of strategic planning and defined goals and objectives for each level in the agency. Successful asset management should include activities and processes that ensure that goals are consistently being met in an effective and efficient manner. AASHTO has developed a guide for asset management implementation in order to guide agencies on best practices for asset management implementation. This guide, *AASHTO Transportation Asset Management Guide: A Focus on Implementation* has outlined 14 steps that need to be completed for transportation asset management implementation (AASHTO, 2011).

## Setting agency goals and monitoring performance

Implementing sustainable pavement management as an asset management business process requires that an agency sets goals and objectives that include sustainable considerations, and develop measures to monitor the performance and achievement towards the goals.  Agency goals, objectives and performance measures are all key pieces to pavement management that occur at the strategic level. Strategic goals are statements that reflect the expectations and requirements of the legislative and executive offices in charge of the highway agency. Strategic goals are generally very broad, and may change as leaders of the executive and legislative branches of state or local government change office. In order to meet the goals, a set of strategic objectives are developed. Strategic objectives are targeted performance (e.g., pavement condition) levels that act as a way to link the strategic plan and performance goals. In order to connect the agencies strategic objectives with the current condition of the network, a number of performance measures are developed. Performance measurement is a process for collecting and reporting information regarding the performance of an asset or organization. Performance measurement is how organizations, public and private, measure the quality of their activities and services. Data collection and interpretation, along with robust decision support tools, are important pieces to monitoring performance and aligning an agencies decision with their goals.

### Data collection

One critical requirement for successful asset management, including a meaningful performance measurement program, is a successful data collection program. Pantelias et al. (2009) discuss the importance of designing the asset management data collection program specifically to meet the agency goals in order to minimize the amount of unnecessary data collected. Data required for pavement management may vary based on the agency goals and performance measures, but includes an accurate inventory of the pavements along with condition, age and construction history data.

The detail of data collected is a function of the level of analysis that will be performed with the data (see Figure x.1). Data for a typical pavement management program is collected at the network level, which implies that the level of detail of the collected data is less than the level of detail that would be used for design. As discussed in Pantelias et al. (2009), decisions that are made at a higher level (i.e. network or strategic level) require data that are aggregated over a much more broad range than lower level decisions (i.e. project level decisions). This typically results in data that is reported in condition values, which are single values that represent an aggregation of all pavement distresses, which are averaged over similarly constructed pavement segments.

### Decision support tools

Sustainable pavement management often requires the use of numerous decision support tools in order to provide the managing agency with methods to evaluate the various management alternatives. An example of one such decision support tool is the use of life cycle cost analysis (LCCA) as a method to evaluate the long term economic costs of a given management alternative. The purpose of decision support tools is to provide a platform for comparison of many alternatives, and several tools are discussed in the following sections.

### Economic Analysis

Determining the economic impacts of pavement management policies and interventions is an important step towards guaranteeing optimal life cycle performance of pavements. Agencies in charge of managing pavements are often faced with budget constraints, thus selected treatments must demonstrate their technical and cost effectiveness in addressing short-term and long-term structural and functional deficiencies. Criteria for evaluation may be grouped in costs and benefits (Hudson, et al., 1997). Costs include agency or direct costs (e.g., initial capital, maintenance, salvage return, financing), and non-agency or indirect costs (e.g., user costs, environmental impact, disruption). Benefits are typically determined in terms of increased functionality of the pavements, such as increased pavement condition and capacity. Further benefits such as income generation or increased mobility could arise from implementing a particular project, however these benefits are typically not addressed in modern cost benefit analysis for pavements.

LCCA is an economic analysis method for comparing long term investment options, generally with the purpose of comparing the overall long-term costs of several management alternatives. The use of LCCA in pavement design and management is discussed thoroughly in a technical brief released by FHWA (FHWA, 1998). The first step in conducting an LCCA is to develop several management alternatives, along with the analysis time frame, and activity timing and condition triggers for specific maintenance actions. Next, agency and user costs should be developed for each of the activities over the analysis time frame. User costs may also include the marginal increase in fuel consumption that results from an increase in pavement roughness between the specific activities. The next step in an LCCA is to develop expenditure streams, which include the discounted costs over time, and compute the net present value for each alternative.

LCCA can be categorized as either deterministic or probabilistic. Deterministic LCCA is a type of analysis that uses fixed values in the analysis, whereas a probabilistic approach uses distributions to represent the variability of the various input and output parameters used in the analysis. For example, a deterministic approach may define the cost for a particular action as *x*, where the probabilistic approach would define the cost as a distribution with a mean value of *x* and a given standard distribution. This concept is further illustrated in Figure x.2.

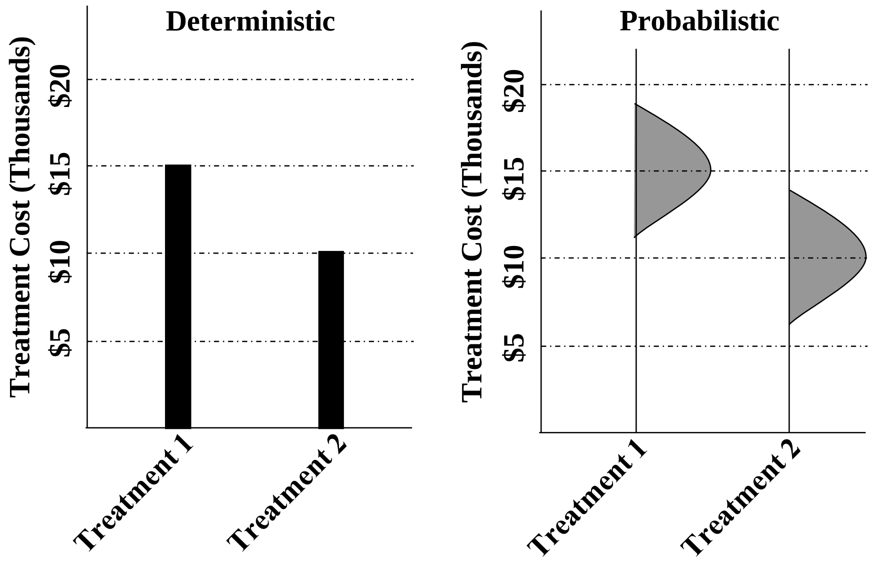


**Figure x.2 Deterministic and Probabilistic LCCA**

A benefit to the probabilistic approach over the deterministic approach is that risk can be evaluated from the outputs of the probabilistic LCCA. This is because the solution reached from the probabilistic approach is a distribution representing the possible outcomes along with the probability of each outcome. Several tools are available for a probabilistic LCCA, such as the FHWA program RealCost (FHWA, 2013). Chen and Flintsch (2012) proposed a fuzzy logic based model to enhance the probabilistic LCCA approach by providing a method to better interpret some of the inherently ambiguous inputs.

Another economic tool available for evaluating pavement management decisions is cost benefit analysis (CBA). The approach to CBA is to first evaluate the costs of the pavement management alternative, then the benefits of each alternative are calculated, and finally each alternative is compared on the basis of both its costs and benefits (e.g. comparing the costs divided by the benefits). Hudson et al. (1997) describe this process in more detail. The CBA approach differs from LCCA because costs are offset by benefits, meaning higher costs may be compensated for by higher benefits. Similar to LCCA, CBA can be conducted either deterministically by using expected costs and benefits, or probabilistically as described in Butt et al. (1994). Lamptey et al. (2005) discuss several other economic tools for use in pavement management,

### Environmental analysis tools

The tool that is generally understood to be the most appropriate for studying the environmental impacts in terms of greenhouse gas emissions or energy consumption of the pavement system is the lifecycle assessment (LCA). The purpose of a pavement LCA is to quantify the total environmental impact of the pavement throughout the pavements life, which is generally divided into the following five phases (Santero, et al., 2011); (*1*) raw materials and production, (*2*) construction, (*3*) use, (*4*) maintanenance and (*5*) end of life.

LCAs are generally categorized as either process based models, economic input-output models or hybrid (a combination of process based and input-output models). Process based models are based on the resource use and environmental impacts from the main processes of the system under evaluation (Suh, et al., 2004). Generally, the process based LCA can be represented as flow diagrams or matrices describing each process interactions. Economic input-output models are top down hierarchical models which use total factor multipliers based on the national economy to determine embodied effects per unit of production (Lenzen, 2008). Different parameters within the process are weighted based on their contribution, and then broken into more detailed levels until the entire process is defined at an adequate level of detail. Input-output LCA models account for interdependencies between sectors and processes using monetary transactions between the sectors on a national or global economic scale. A more detailed discussion of the LCA types, along with a comparison of strengths and weaknesses can be found in (Santero, et al., 2011).

The most common method for conducting an LCA is a process-based method that is defined by the International Standards Organization (ISO). The ISO outlines a four step approach in their standard ISO 14040 and ISO 14044, Standards for a Process-Based LCA Approach (International Organization for Standardization, 2006). The steps are as follows:

1. Goal and scope. Define the reasons for carrying out the LCA, the intended audience, geographic and temporal considerations, system functions and boundaries, impact assessment, and interpretation methods.

2. Inventory assessment. Quantify life-cycle energy use, emissions, and land and water use for technology use in each life-cycle stage.
3. Impact assessment. Estimate the impacts of inventory results.
4. Interpretation. Investigate the contribution of each life-cycle stage and technology use throughout the life cycle and include data quality, sensitivity, and uncertainty analyses.

Huang et al. (2009) describe the process given in ISO 14040 in more general terms as *(1)* defining the scope, *(2)* performing the LCI to gather all relevant environmental burdens (this is where the majority of the work resides), *(3)* perform a lifecycle impact assessment (LCIA) where the results are presented in such a manner that supports comparison, interpretation of the results or further analysis. Santero et al. (2011) notes an important distinction between life-cycle inventories (LCI's) as the part of an LCA in which the resource use and pollutant releases are quantified and the full LCA which includes an impact analysis and interpretation of the results.

Santero et al. (2011) performed a critical assessment of the current state of pavement LCA's by extensively reviewing available literature on the topic. The researchers identified four attributes of the methodology of the LCA that are essential for comparing the studies, (1) Functional Unit Comparability, (2) System Boundary Comparability, (3) Data Quality and Uncertainty and (4) Environmental Metrics. Functional unit comparability becomes an issue when trying to compare results from studies that evaluate different pavements that facilitate different traffic types across different climates or environmental regions. Essentially, many of the results of LCAs found in literature cannot be directly compared due to the differing functional units (Santero, et al., 2011). The researchers note the omission of the use phase from the majority of pavement LCA's as possibly the most significant shortfall of modern studies. Furthermore, it was noted that a majority of the studies that included maintenance in the system boundaries simplified the maintenance practices to a series of repeated impacts, and did not include practices such as diamond grinding or crack sealing.

The LCA of the raw materials, material production and construction phases of the lifecycle have been the focus of extensive research. For example, Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is a spreadsheet based tool that was developed to account for both economic and environmental factors related to the construction processes of a pavement (Horvath, 2003). Park et al. (2003) evaluated the environmental loads due to the processes throughout the lifecycle of a highway, defined in four stages as: (1) manufacturing of materials, (2) construction, (3) maintenance and (4) end of life (demolition/recycling), but notably the use phase is excluded from the definition of the pavement lifecycle. The researchers focused on energy consumption, then used appropriate factors to translate the energy consumption into equivalent emissions and estimate pollutant discharge into water.

Huang et al. (2009) evaluated modern LCA data and methods pertaining to pavements, then applied the techniques to an airport asphalt paving project. The research identified major shortcomings with many modern LCA methods, such as their inapplicability to pavements, and proposed an updated LCA model based on the processes contained within asphalt pavement construction. The researchers identified the quality of the gathered data as an important parameter that should be continuously improved as new data arises. The results of an example LCA using the developed model proved insightful for decision makers and understanding the critical factors that contribute to adverse environmental impacts (Huang, et al., 2009). Furthermore, the detailed unit processes involved in the construction of an asphalt pavement were represented in the paper by Huang et al. (2009).

Some other examples of pavement LCAs are described in Patrick and Arampamoorthy (2010), Weiland and Muench (2010), Wang et al. (2012) and Zhang et al. (2010). The work by Patrick and Arampamoorthy concluded that potentially significant savings in energy consumption and emissions can be achieved through waste minimization (Patrick & Arampamoorthy, 2010). Weiland and Muench (2010) compared three different options of replacing a Portland Cement Concrete (PCC) pavement, including two HMA options and one PCC option, and demonstrated the use of several tools for conducting LCA's, such as the US Environmental Protection Agency's (EPA) NONROAD model for construction equipment and the EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (Weiland & Muench, 2010). Wang et al. (2012) and Zhang et al. (2010) both presented methodologies for including limited factors of the pavement use phase into the LCA by linking the pavement condition to vehicle rolling resistance.

Much of the research pertaining to the use phase of the pavement has focused on quantifying the effect of rolling resistance on emissions and energy consumption from vehicles travelling on the pavement. Several research projects have quantified the impact of pavement properties on rolling resistance, and some research has shown that in all driving conditions, an overall average of 25 percent of fuel consumption is expended on rolling resistance leaving 75 percent to overcome air drag and inertia (Izevbekhai, 2012). Thus, if the rolling resistance of a pavement were reduced, the vehicle fuel consumption along that pavement would be reduced. Furthermore, a 10 percent reduction in rolling resistance can lead to between a 1 and 2 percent reduction in fuel consumption, which also leads to a reduction of greenhouse gas emissions (Evans, et al., 2009), (Transportation Research Board: Committee for the National Tire Efficiency Study, 2006). The tire-pavement interaction is the main factor in rolling resistance, and is impacted by several variables such as: macro-texture, pavement stiffness, roughness, rutting and the transversal slope of the pavement. Relatively good relationships have been developed to determine the impact of roughness (IRI) and macro-texture (MPD) on a vehicles rolling resistance, whereas relationships between rolling resistance and other pavement surface factors have not been adequately developed at this time.

Two commonly used models relating pavement properties to rolling resistance and fuel consumption have been developed in recent years. One model was developed by Chatti and Zaabar by calibrating the HDM 4 models for vehicle operating costs (Chatti & Zaabar, 2012). The fuel consumption model was calibrated over several pavements in the state of Michigan using six different vehicles: a medium car, sport utility vehicle, van, light truck, and an articulated truck. The details of the model can be found in the NCHRP report 720 (Chatti & Zaabar, 2012), along with a Microsoft Excel™ tool developed as part of the NCHRP project that can be used to estimate vehicle operating costs (as well as vehicle fuel consumption) given several conditions.

A second model was developed as part of an international collaboration, Models for rolling resistance In Road Infrastructure Asset Management systems (MIRIAM). Some outcomes and models developed as a part of MIRIAM are described in detail in Hammarstrom et al. (2011) and Wang et al. (2012). The model was developed based on empirical results from coast down measurements in Sweden, and includes impacts of: pavement roughness, macrotexture, temperature, speed, horizontal curvature and the road grade. The model was developed for three vehicle types, a car, a heavy truck and a heavy truck with a trailer.

### Equity and other social considerations

One fundamental objective of any transportation system is to provide a safe and equitable connection between society and the services it needs while also minimizing any impacts that adversely impact any portion of society. Thus, it is clear that equity must be evaluated as an integral part of sustainability. Muench et al. (2010) describe equity as, "political or mandated processes for ensuring environmental justice, cultural and aesthetic considerations". The California Energy Commission has described environmental justice as a way of ensuring all people, regardless of their socio-economic status, race or any other factors, enjoy equally high levels of environmental quality (California Energy Commission, n.d.). Whereas environmental impacts of infrastructure have been well documented, the social and equitable factors resulting from investment in infrastructure management are less developed. Some research has shown the extent of a society's well-being has been directly correlated to the extent of that society's infrastructure (Chamorro & Tighe, 2009). The interconnected systems of highways, bridges, pipelines and dams have made the changes in social behaviors possible by providing mobility, safe drinking water, waste management, and stable structures. The presence of an extensive road network allows people in rural areas to have access to health care markets, and financial resources that are typically more prevalent in urban areas, and clean drinking water is a basic need for the health of all people. This concept is discussed further in Jeon et al. (2006) on the basis of evaluating transportation sustainability within four transportation agencies. One finding in Jeon et al. (2006) was that no transportation agency measured the impact of equity by evaluating the relative accessibility of the population to basic services.

Several aspects directly related to equity in pavement management are addressed in sustainable rating tools for highways such as Greenroads (Muench, et al., 2010). Some examples of social related considerations on which pavement management practices can have a direct impact include metrics to improve human health and safety, and improve access and mobility. Some important considerations in equity also coincide with environmental concerns, such as the reduction in air pollution, minimizing the use of non-renewable resources (minimize impact on future generations), and minimizing water use during construction.

### Multi-attribute decision making

The field of pavement management, or more broadly infrastructure management, consists primarily of investment tradeoffs considering multiple competing objectives and multiple stakeholders. Therefore, an important tool to consider for sustainable pavement management is multi-attribute decision making. Important aspects in multi-attribute decision problems are multiple objectives (i.e. multiple criteria and desired levels of attainment for each criterion), constraints for the criteria, and preference functions or weighting values used to compare the criteria. Solutions for multi-criteria problems are given by a set of non-dominated solutions (as opposed to a single optimal solution), and thus some judgment or preference function must be evaluated to select the preferred solution from amongst the non-dominated set.

Several methods exist for solving multi-attribute problems. For example, Wu and Flintsch (2009) present a method for replacing traditional deterministic constraints with stochastic constraints before developing the set of non-dominated solutions. Giustozzi et al. (2012) proposed a method of rescaling each criterion between zero and one, weighting each criterion in terms of preference, and then summing the product of each rescaled criteria and criteria weight to determine the best alternative. Some other methods for solving multi-attribute decision problems are discussed in more depth below.

Galenko et al. (2013) presented the application of utility theory in highway asset management strategy development, and proposed that optimizing resource allocation in asset management should be based on the maximization of the overall utility attributed to the assets. Utility theory is a method for solving multi-atribute problems in which a decision maker's values are quantified over a range of feasible outcomes, then the values are combined with the corresponding probabilites of each outcome to form a set of utility values. The motivating factor behind utility theory is that if an appropriate utility is assigned to each possible outcome, and the expected utility of each alternative is calculated, the best alternative is the one that maximizes the overall utility (Keeney & Raiffa, 1993). The strength of utility theory is that the relative strength of preference between possible outcomes for each variable is used to determine the best alternative from the set of possible alternatives. In other words, it is not assumed that increasing a variable four times the original amount has double the value of increasing the original amount by two times.

Li and Sinha (2004) presented a method for using utility theory in transportation asset management decision making. The utility curves for several individuals were assessed over a number of parameters through questionnaires and interviewing techniques. The utility functions were then aggregated using an ordinary least squares regression technique (OLS) technique. Another application of utility theory in transportation decision making was presented by Zietsman et al. (2006). In this case, the utility curves were assumed to have particular shapes and curvatures at certain points based on typical human preferences.

One important aspect of multi-criteria problems is the aggregation of preferences among many decision makers. The importance of comparing the preferences between the many decision makers is because it is possible that different solutions are seen as optimal to different decision makers. One method for comparing preferences is through preference rank aggregation. The use of ranking methods in transportation decision making has been demonstrated when evaluating the alignment of a proposed new highway. Stich et al. (2011) developed a number of proposed alignment alternatives using GIS tools, and then utilized a public informational meeting to have the voters rank the projects given all of the relevant information (i.e. wetland impact, noise and air pollution, etc.) about each alternative. In this case, the highway agency acts as the final decision maker, and the rankings of the voters are used in the final ranking of the projects. One policy related benefit that the research cited about gathering the stakeholders' preferences was the possibility of streamlining project delivery times by addressing concerns of the public before they arise, instead of retroactively trying to mitigate the problems and concerns.

Lahdelma et al. (2000) describes the use of ranking alternatives among the many stakeholders as an important key to environmental decision making. The authors discuss the importance of gathering the ranking among the stakeholders given that environmental planning is of strong interest to many stakeholders beyond just the decision making organization. Furthermore, the authors point to the importance of clearly defining the alternatives and criteria, as well as how each criterion is measured so that no ambiguity exists among the stakeholders. Finally, it is discussed in the paper that the rankings of the many alternatives among the many stakeholders can be used to develop new alternatives that more closely reflect the values of the many stakeholders (Lahdelma, et al., 2000).

Another example of ranking is by the use of the analytical hierarchy process (AHP). Smith and Tighe (Smith & Tighe, 2006) describe using AHP as a tool for assessing user preferences of maintenance and rehabilitation decision making in transportation asset management. A large subset of road users were identified and surveyed to determine their preferences for many different criteria related to road maintenance and rehabilitation. The preferences were then aggregated by using a simple averaging technique, and the AHP technique was used to evaluate the criterion that was considered most important by user groups, and how the user groups would weight various alternatives.

### Incorporating Sustainability into the Pavement Management Decision Making Process

Beyond defining pavement sustainability and sustainable performance measures is the critical step of implementing sustainability into the pavement management decision making process. This includes incorporating sustainability as a fundamental business practice within the agency where considerations about project selection, treatment type selection, lifecycle management, and the tradeoff between the triple bottom line (economic, environmental and social impacts) are addressed in the initial decision processes. Sustainability can be included at all three levels of the pavement management process, and each will be discussed in more detail in the following sections.

### Project level

Decisions about pavement design, construction practices and scheduling, material acquisition, and congestion management plans are just a few examples where sustainability can be implemented at the project level. For example, Diefenderfer et al. (2012) discuss an *in situ* pavement recycling process used on part of a Virginia interstate that attempted to minimize the use of virgin construction materials, minimize construction costs and minimize the impact on the travelling public through a use of innovative management practices. In the case discussed by Diefenderfer et al. (2012), the lowest lifecycle cost option that was considered also had the most environmental benefit, and the least adverse social impact (as measured by travel time interruption, depletion of virgin materials and reduction of construction waste).

Another aspect that should be considered at the project level is the impact of the maintenance on the rolling resistance and vehicle operating costs from a lifecycle perspective. For example, the minimal maintenance cost alternative for rehabilitating a pavement may be to apply light maintenance for a defined number of intervals. However, a more extensive rehabilitation may reduce the rate of deterioration of the condition and the rate of increase in roughness for a road, which in turn leads to a reduction in the overall vehicle operating costs, fuel consumption and vehicle emissions for the pavement.

Pavement type selection and design are fundamental concerns during project level pavement management. Pavement type selection refers to choosing the most appropriate paving material (i.e. Portland cement concrete or asphalt concrete) to be used during construction. Typically, this choice comes down to the result of a lifecycle cost analysis, the availability of local construction materials, and the familiarity of local contractors with constructing using the materials (Hallin, et al., 2011). However, many more factors can be included, and their tradeoffs considered, in order to make the pavement type selection process more sustainable. For example, given the models that relate vehicle fuel consumption to pavement properties, a lifecycle assessment can be conducted for each paving material in consideration. It is clear that values for the surface texture and pavement roughness will change over time at different rates for different material types, thus resulting in different fuel consumption, emissions profiles and total vehicle operating costs for each pavement over a defined time frame (Chatti & Zaabar, 2012). Secondly, maintenance practices and the availability of local materials (virgin or recycled) differ for each pavement type, which will impact the results of any assessment of sustainability during pavement type selection (Patrick & Arampamoorthy, 2010). Finally, the impact of the pavement surface characteristics on effects such as carbonation, pavement lighting requirements and the urban heat island effect (considering pavement albedo) should also be considered during pavement type selection (Santero, et al., 2011).

### Network level

Sustainable pavement management practices at the network level includes designing maintenance strategies and selecting projects while considering impacts related to the triple bottom line of sustainability. This may include modifying the objectives of a network level analysis so that a multi-criteria approach is considered during the unconstrained needs analysis and optimization. Generally, the resulting multi-objective decision problem arising from the network level pavement management process is converted to a single objective problem by treating some of the objectives as the constraints (Wu & Flintsch, 2009). In this way, an agency seeks to maximize or minimize one particular objective (e.g. minimizing the cost divided by the performance of the pavement condition) subject to constraints that arise from the original objectives (e.g. budgetary constraints or constraints defining a minimum allowable pavement condition).

A shortcoming with the single criterion approach is that when objectives are reformulated as constraints, the resulting analysis becomes non-compensatory (Goodwin & Wright, 1998). In other words, undesirable values in the newly formulated constraints are no longer compensated for by highly desirable values in the objective values. Consequently, there is no longer a guarantee that the selected value is non-dominated, and a more optimal value may exist depending on the extent to which the constraints are relaxed. A non-dominated solution is a solution in which it is not possible to better the outcome of one variable without making worse the values of the remaining variables. Secondly, the non-compensatory analysis tends to bias the results to the parameter that is chosen as the objective function, thus rendering other objectives as lower level considerations.

Giustozzi et al. (2012) presented a multi-criteria approach for evaluating preventive maintenance activities that included costs, performance and environmental impact measures during the analysis. Several maintenance strategies were evaluated based on the measures, and a method for comparing all strategies by rescaling each measure was developed. The first step in the analysis was to define the strategies, as well as the associated lifecycle cost for each strategy. Then the performance was calculated as the area beneath the curve defining the condition as a function of time. Finally, the energy consumption and emissions related to each strategy were calculated for the materials and construction phase of the LCA. The measures were all scaled between zero and one, with one representing the worst case and zero representing the worst case value, and the rescaled values were weighted and summed to calculate a single index.

Bryce et al. (2014) presented a probabilistic approach to include the use and maintenance phase into the network-level pavement management process. A Monte Carlo simulation was used to develop histograms of energy consumption for several levels of pavement maintenance and rehabilitation, as well as distributions representing the energy consumption from vehicles traveling along the pavement. The models developed by Chatti and Zaabar (2012) were used to estimate the additional fuel consumption due to an increase in pavement roughness. A benefit of using the probabilistic approach that was cited by Bryce et al. (2014) is that the relative risk associated with each pavement management decision can be evaluated along with the expected value for each criterion.

### Strategic level

Successful implementation of pavement management requires the establishment of strategic planning and defining goals and objectives, which all occurs at the strategic level. The AASHTO Asset Management Implementation Guide (AASHTO, 2011) discusses the importance of planning at the strategic level. Strategic planning is an organization's process of defining its strategy, or direction, and making decisions on allocating its resources to pursue this strategy. Strategic planning should clarify the goals, mission, vision, value and strategies of the organization, as well as the performance measures used to evaluate progress toward each of the goals.

Defining performance measures that link an agencies goals and objectives with a level of achievement is critical for successful sustainable pavement management. In order to demonstrate this, the goals, objectives and measures that can be related to pavement management for the Georgia Department of Transportation (GDOT) are presented in Table x.1. The goals, objectives and measures for GDOT were taken from a document published online that defines the agencies strategic plan (GDOT, 2011). Furthermore, the performance measures are published online and updated as new data becomes available. Although GDOT does not have any objective specifically related to the environmental component of sustainability, it is clear from the structure of Table 1 how such an objective can be developed under a strategic goal.

**Table x.1. GDOT Strategic Goals, Objectives and Performance Measures**

| Strategic Goal | Strategic Objectives | Performance Measures |
| --- | --- | --- |
| Taking care of what we have in the most efficient way possible | Maintain Interstates at a condition ≥ 75 | Average condition rating on all Interstates. |
| | Maintain State owned multi-lane non-interstate routes at a condition ≥ 70 | Average condition Rating on multi-lane non-interstate routes. |
| | Maintain State-owned bridges such that they meet a determined standard as defined by their Strength and their Condition | Percent of State-owned bridges that meet or exceed a determined standard based on Strength and Deck condition; defined as follows:<br>- Deck Condition on<br>Interstates ≥ 7<br>U.S. Routes ≥ 6<br>State Routes ≥ 5<br>Off-System State-Owned ≥ 5<br>or<br>- Interstates, U.S. Routes, State Routes and Off-System State owned bridges that are not posted (Posting Code = 5)<br>Target is ≥ 85% of the bridges meeting this criteria<br>with no Interstate bridge postings |
| Planning and Constructing the best Set of Mobility-Focused Projects we can, On Schedule | Complete Plan Development and Construction of projects per the programmed year in the currently approved Statewide Improvement Program | Percent of right of way Authorized on Schedule per the approved Statewide Improvement Program with a target of 80% |
| | | Percent of authorized on schedule per the approved Statewide Improvement Program with a target of 80% |
| | | Percent of Projects under Construction completed on Schedule |
| | | Comparison of award amount to final cost |
| | Maintain or improve the percentage of survey respondents that give GDOT a grade of A or B for meeting transportation needs in Georgia (Customer Service Objective) | Percent of Public Opinion Poll survey respondents that give GDOT a grade of A or B in meeting transportation needs in Georgia |

## Making Pavement Management Systems Sustainable With an Organization

The structure of an organization is critical to successful sustainable pavement management and the implementation of sustainable objectives into the pavement management business processes. Integrating sustainability considerations into pavement management implies collecting and managing data that has not traditionally being part of pavement management, such as the environmental input and outputs of the various process. As with any infrastructure management system, a pavement management system relies on three fundamental components: processes, people and technology. There must also be a commitment to adequate funding. If any of these are lacking, there is a high probability that the system will not be successful (Flintsch, et al., 2007).

The best technology in the world will ultimately fail if implemented in an environment where there are no people to run it, or where the business processes are not in place to utilize it. Furthermore, executives and managers need to be demonstrably committed to the system, both in their relations with external stakeholders and internally in their agency through good management principles. Policies should explicitly state the goals and objectives of the organization in regard to pavement asset management, and procedures should detail exactly how the pavement management processes can help achieve these goals. There has to be a specific organizational unit that have explicit responsibility for the processes and data, and is staffed with well-qualified and trained personnel, who are pro-active in developing and expanding the system. Finally, the data collection equipment and hardware and software should be fit for purpose, actively used, and properly maintained and managed and managed. These elements are essential in ensuring sustainability of the pavement management process (Flintsch, et al., 2007).

## Conclusions

Sustainable pavement management as a business practice is about facilitating pavement investment tradeoffs considering the triple bottom line of sustainability during the design, construction, maintenance and rehabilitation of pavements. The consideration of sustainability goals for managing pavement assets requires setting targets for and measuring the economic, environmental, and social performance of the competing pavement investments. Many decision support tools have been developed to inform the tradeoff between these factors; these include tools for LCCA and LCA. Tools for handling the social impact are less developed but are starting to show in the research literature. Factors that are key to successful sustainable pavement management include management buy-in, maintaining clear strategic goals, quantifiable strategic objectives, and clear performance measures, appropriate technologies for data collection and analysis, and well-trained and motivated personnel.

## References

AASHTO, 2011. *Transportation Asset Management Guide, A Focus on Implementation.* Washington, DC: American Society of State Highway and Transportatoin Officials.

ASCE, 2012. *American Society of Civil Engineers.* [Online]
Available at: http://www.asce.org/sustainability/
[Accessed 8 October 2012].

ASTM International, 2011. *ASTM Standard D6433: Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys.* West Conshohocken, Pennsylvania: ASTM International.

Bryce, J. et al., 2014. *Probablistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements.* Washington, D.C., s.n.

Butt, A., Shahin, M., Carpenter, S. & Carnahan, J., 1994. *Application of Markov Process to Pavement Management Systems at the Network Level.* San Antonio, TX, s.n.

California Energy Commission, n.d. *Environmental Justice.* [Online]
Available at: http://www.energy.ca.gov/public_adviser/environmental_justice_faq.html
[Accessed 25 January 2014].

Cambridge Systematics, Inc., 2002. *Transportation Asset Management Guide, Volume 1,* Washington, DC: American Association of State Highway and Transportation Officials.

Chamorro, A. & Tighe, S. L., 2009. Development of a Management Framework for Rural Roads in Developing Countries. *Transportation Research Record of the National Academies,* pp. 99-107.

Chatti, K. & Zaabar, I., 2012. *Estimating the Effects of Pavement Condition on Vehicle Operating Costs,* Washington, DC: Transportation Research Board of the National Academies.

Chen, C. & Flintsch, G., 2012. Fuzzy Logic Pavement Maintenance and Rehabilitation Triggering Approach for Probabilistic Life Cycle Cost Analysis. *Transportation Research Record: Journal of the Transportation Research Board of the National Academies,* Volume 1990, p. 80–91.

Diefenderfer, B. et al., 2012. In-Place Pavement Recycling on I-81 in Virginia. *Transportation Research Record: Journal of the Transportation Research Board,* Volume 2306, p. 21–27.

Evans, L. R. et al., 2009. *NHTSA Tire Fuel Efficiency Consumer Information Program Development: Phase 2 – Effects of Tire Rolling Resistance Levels on Traction, Treadwear, and Vehicle Fuel Economy,* East Liberty, OH: National Highway Traffic Safety Administration.

Federal Highway Administration, 2013. *Transportation Performance Management: Life-Cycle Cost Analysis Software.* [Online]
Available at: http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm
[Accessed 1 December 2013].

FHWA, 1998. *Life Cycle Cost Analysis in Pavement Design Demonstration Project 115 – Participant Handbook,* s.l.: FHWA.

Flintsch, G., McPherson, K. & Bennett, C., 2007. *Making Road Management Systems Successful.* Washington, DC, s.n.

Flintsch, G. W. & Chen, C., 2004. "Soft Computing Applications in Infrastructure Management. *ASCE Journal of Infrastructure Systems,* Volume Vol. 10, pp. 157-166.

Galenko, A., Pilson, C. & Scheinberg, T., 2013. *Identifying the Optimal Mix of Highway Asset Maintenance Activities based on Performance Targets or Budget Constraints*. Washington, DC, Proceedings of the Transportation Research Board of the National Academies.

GDOT, 2011. *Transportation Asset Management - The Strategic Direction of Georgia Department of Transportation,* Atlanta, GA: Division of Orginizational Performance Management.

Giustozzi, F., Crisino, M. & Flintsch, G., 2012. Multi-attribute Life Cycle Assessment of Preventive Maintenance Treatments on Road Pavements for Achieving Environmental Sustainability. *International Journal of Lifecycle Assessment,* Volume 17, pp. 409-419.

Goodwin, P. & Wright, G., 1998. *Decision Analysis for Management Judgment, 2nd ed.*. West Sussex: John Wiley & Sons,.

Hallin, J. et al., 2011. *Guide for Pavement Type Selection: NCHRP Report 720,* Washington, DC.: Transportation Research Board of the National Academies .

Hammarström, U., Eriksson, J., Karlsson, R. & Yahya, M., 2011. *Rolling Resistance Model, Fuel Consumption Model and the Traffic Energy Saving Potential fom Changed Road Surface Considtions,* Linköping: Swedish National Road and Transport Research Institute.

Horvath, A., 2003. *Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements,* Berkeley: University of California Transportation Center.

Huang, Y., Bird, R. & Heidrich, O., 2009. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production,* Volume 17, pp. 283-296.

Hudson, Haas & Uddin, 1997. *Infrastructure management: integrating design, construction, maintenance, rehabilitation, and renovation.* New York: McGraw Hill.

International Organization for Standardization, 2006. *Environmental Management - Life Cycle,* s.l.: ISO Standard 14040.

Izevbekhai, B., 2012. *Concrete Paving and Texturing for Sustainability.* Minneapolis, MN: Presented at Center For Transportation Studies Research Conference.

Jeon, C. M., Amekudzi, A. A. & Vanegas, J., 2006. Transportation System Sustainability Issues in High, Middle and Low Income Economies: Case Studies from Georgia (U.S.), South Korea, Colombia, and Ghana. *ASCE Journal of Urban Planning and Development,* 132(3), pp. 172-186.

Keeney, R. & Raiffa, H., 1993. *Decisions With Multiple Objectives: Preferences and Value Tradeoffs.* Cambridge, UK: Cambridge University Press.

Lahdelma, R., Salminen, P. & Hokkanen, J., 2000. Using Multicriteria Methods in Environmental Planning and Management. *Environmental Management Vol. 26, No. 6,* pp. 595-605.

Lamptey, G., Ahmad, M., Labi, S. & Sinha, K., 2005. *Life Cycle Cost Analysis for INDOT Pavement Design Procedures,* West Lafayette: Purdue University.

Lenzen, M., 2008. Errors in Conventional and Input-Output–based Life-Cycle Inventories. *Journal of Industrial Ecology,* pp. 127-148.

Li, Z. & Sinha, K. C., 2004. *Methodology for the Development of a Highway Asset Management System for Indiana: Publication FHWA/IN/JTRP-2003/21,* West Lafayette, Indiana: Joint Transportation Research Program, Indiana Department of Transportation and Purdue University.

Muench, S. T., Anderson, J. & Bevan, T., 2010. Greenroads: A Sustainability Rating System for Roadways. *International Journal of Pavement Research and Technology,* 3(5), pp. 270-279.

Pantelias, A., Flintsch, G. W., Bryant, J. W. & Chen, C., 2009. Asset Management Data Practices for Supporting Project Selection Decisions. *Public Works Management Policy,* 13(3), pp. 239-252.

Park, K., Hwang, Y., Seo, S. & Seo, H., 2003. Quantitative Assessment of Environmental Impacts on Life Cycle of Highways. *ASCE Journal of Construction Engineering and Management,* pp. 25-31.

Patrick, J. & Arampamoorthy, H., 2010. *Quantifying the benefits of waste minimisation - NZTA Report 406,* Wellington, NZ: NZ Transport Agency.

Santero, N., Masanet, E. & Horvath, A., 2011. Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling,* pp. 801-809.

Shahin, M., 2005. *Pavement Management for Airports, Roads, and Parking lots.* New York: Springer.

Smith, J. & Tighe, S., 2006. The Analytical Hierarchy Process as a Tool for Infrastructure Management. *Transportation Research Record, Journal of the Transportation Research Board,* Volume 1974.

Stich, B., Holland, J. H., Noberga, R. A. & O'Hara, C. G., 2011. Using multi-criteria decision making to highlight stakeholders' values in the corridor planning process. *The Journal of Transport and Land Use,* 4(3), pp. 105-118.

Suh, S. et al., 2004. System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science and Technology,* pp. 657-664.

Transportation Research Board: Committee for the National Tire Efficiency Study, 2006. *Tires and Passenger Vehicle Fuel Economy: Informing Consumers, Improving Performance TRB Special Report 286,* Washington, DC: Transportation Research Board of the National Academies.

Wang, T. et al., 2012. Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production,* pp. 86-96.

Weiland, C. & Muench, S., 2010. Life-Cycle Assessment of Reconstruction Options for Interstate Highway Pavement in Seattle, Washington. *Transportation Research Record,* p. 18–27.

Wu, Z. & Flintsch, G., 2009. Pavement Preservation Optimization Considering Multiple Objectives and Budget Variability. *ASCE Journal of Transportation Engineering,* 135(5), pp. 305-315.

Zhang, H. et al., 2010. Dynamic Life-Cycle Modeling of Pavement Overlay Systems: Capturing the Impacts of Users, Construction, and Roadway Deterioration. *ASCE Journal of Infrastructure Systems,* pp. 299-309.

Zietsman, J., Rilett, L. & Kim, S.-J., 2006. Transportation Corridor Decision Making with Muti Attribute Utility Theory. *International Journal of Management and Decision Making,* 7(2/3), pp. 254-266.