A Systematic Assessment of Road Pavement Sustainability through a Review of Rating Tools

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ABSTRACT

Pavements are engineered systems present in every modern society, and they have significant environmental, economic and social impacts. In an effort to promote more sustainable decisions regarding pavement design, construction and management, several pavement sustainability assessment tools have been developed. This research reviewed some of these tools and found that many of them do not treat the pavement as a system; instead, they seek to optimize individual aspects of the pavement in an effort to increase its sustainability. Therefore, a framework for analytically assessing the system outcomes towards sustainable objectives is presented and applied for modern pavement sustainability assessment. The results suggest that this framework provides a way to systematically include data in the evaluation of the outcomes of pavement management decisions towards achieving sustainable objectives.

HIGHLIGHTS

- We critically review the current state of pavement sustainability assessment
- A framework to support decision making for more sustainable outcomes is developed
- We conclude that a systems-based approach to measure outcomes is needed for pavements

KEYWORDS: Pavements, Sustainability Assessment, Lifecycle Assessment, Infrastructure Management, Performance Management

1. Introduction

Road pavements are one of the most common forms of public infrastructure in the world, and require continuous investments and improvements to stay serviceable. This is evident by the fact that the U.S. public spends more than 184 billion dollars annually on maintaining and expanding the pavement network (CBO, 2016). In England, more than 15 billion pound sterling is planned to be invested specifically to increase capacity and condition of the road network (UK Department for Transport, 2014). Furthermore, adaptation to global climate change is expected to create a need for a significant increase in investments towards pavement maintenance (Chinowskya et al., 2013, Qiao et al., 2015). These cases reflect substantial investments anticipated for road networks through improvement, maintenance and rehabilitation of pavements. Therefore, a critical step in advancing towards more sustainable infrastructure is to promote more sustainable pavement management practices, which can be facilitated by defining performance measures for sustainability related to paving activities and developing tools to evaluate sustainable performance. In light of this, the objective of this paper is to present a review of current pavement sustainability assessment methods and offer recommendations to develop an analytical approach to assess pavement sustainability for decision support.

Given that pavements are material intensive assets, a large focus in pavement sustainability has been on the use of recycled materials in road construction (Huang et al., 2007, Hossain et al., 2016). Reducing the energy intensiveness of pavements has also been a focus of considerable research, which has resulted in methods to lower asphalt manufacturing temperatures (Vidal et al., 2013) and to substitute portland cement by partially replacing it with supplementary materials (Nassar et al., 2013). In order to quantify the impacts of resource consumption associated with pavements, several pavement life cycle assessment (LCA) frameworks have been proposed (e.g., Loijos et al. (2013), Butt et al. (2014) and Santos et al. (2017)), assumptions in LCA methodologies have been evaluated (e.g., Huang et al. (2013)), and results from several LCA studies have been reported (e.g., Ventura et al. (2008), Noshadravan et al. (2013) and Santos et al. (2015)). Environmental considerations, however, are only one aspect of sustainability sciences (Sala et al. 2013), and a more holistic assessment is necessary to understand the sustainability of pavements.

Several sustainability assessment tools have been developed for civil infrastructure or road projects, such as the Civil Engineering Environmental Quality (CEEQUAL) guidelines (CEEQUAL, 2013) and the Greenroads program (Muench et al., 2010). However, when viewed specifically through the lens of pavements, they tend to be overly general and many categories defined for assessment do not pertain to pavements or paving activities. Paving activities have narrower boundaries than road construction activities, and thus, require less generalization in order to capture the effects they have on sustainability objectives. In other words, the sensitivity of these systems to pavement construction activities may be low. Important features of road sustainability assessment, such as road geometry and access issues, are not a part of pavement maintenance and rehabilitation processes. If the boundaries are expanded to include issues such as geometry and access, then the pavement project becomes a road construction project.

In order to address pavements in particular, a smaller subset of pavement-related sustainability assessment tools has been developed. These tools, however, also experience several shortcomings, such as: (1) they were developed using a bottom-up approach based on highly regionalized materials and practices thus limiting their use by a wider audience, (2) they were developed based on practices considered sustainable without recommending techniques to analytically measure the outcomes of implementing the practices, or (3) they neglect criteria for which there is no standardised analytical measure, thus measuring sustainability only in terms of what can be systematically calculated. Despite the shortcomings of current pavement sustainability assessment tools, they are still seen as valuable tools for informing the current state of practice towards more sustainable solutions because they encourage the incorporation of sustainable development principles (Johansson, 2011).

1.1. Objective and Methodology

Current pavement sustainability assessment tools are beneficial because they help decision makers identify areas where sustainability can be improved during the design and construction phases, but they lack the framework for measuring the resulting impacts of the decisions made as part of this process. In order to build on the existing state of pavement sustainability assessment, the objective of this paper is to critically review several methods for conducting a pavement sustainability assessment and then to recommend an approach for analytically measuring sustainability-related impacts of pavement maintenance and rehabilitation to support descision making. Sustainability objectives and evaluation criteria were collected from several pavement sustainability assessment tools and were used to derive a set of general objectives for increasing the level of pavement sustainability. The objectives were then layered into a hierarchy, and indicators for performance towards each of the objectives were proposed to measure outcomes analytically. The proposed analytical approach can be used within a performance-based decision-making framework to evaluate the impacts of practices through iterative feedback in order to influence sustainable outcomes.

2. Background

Sustainable design and management of civil infrastructure continues to increase in importance with an increasing body of knowledge that demonstrate effects such as the growing understanding of anthropogenic impacts on global climate change, as well as the continued development of models relating economic and social benefits to infrastructure development. In essence, civil infrastructure has effects on the environmental, economic and social state. In terms of environmental impacts, it is widely observed that approximately one quarter of all CO_2 emissions globally originate within the transportation sector (UNECE, 2014). Furthermore, it has been demonstrated that future infrastructure expansion has the potential to contribute substantially to climate change through increased greenhouse gas emissions (Davis et al., 2010). In terms of economic investments, infrastructure maintenance and expansion contribute considerably to the gross value added to large economies (DBIS, 2013). Finally, it is well recognized that infrastructure is the link that connects human societies with the natural environment and facilitates the growth of welfare within societies (Knaap & Oosterhaven, 2011). Thus, it is clear that practices that lead to an increase in sustainability for infrastructure will impact potential sustainable outcomes within the three components of sustainability: the environment, the economy and society, and over a lifetime of decades, or potentially more.

2.1. Sustainability and Public Infrastructure

Sustainability applied to infrastructure management implies maintaining an acceptable condition while also considering the trade-off between cost, environmental impacts and social impacts of infrastructure investments. Many definitions have been proposed to express sustainability, such as those put forward by the Brundtland Commission (WCED, 1987) and the Council of the European Union (European Commission, 2006), and several benefits and drawbacks have been noted for each of these definitions (Adams, 2006). In general, definitions of sustainability are broad in nature so as not to constrain potential innovations contributing towards the general goal. For example, Muench (2010) defines sustainability as, “a system characteristic that reflects the system’s capacity to support natural laws and human values.” Sustainable development definitions, however, all follow the common theme of development that meets current needs without compromising the future (Adams, 2006). Generally, this is broken into three objectives, which are typically referred to as the triple bottom line of sustainability: (1) enhancing social structures, (2) increasing economic prosperity/equity, and (3) decreasing adverse impacts to the natural environment. The combination of these three objectives can be viewed in two manners: ‘Strong Sustainability’ and ‘Weak Sustainability’ (Adams, 2006). ‘Strong Sustainability’ conveys the fact that no part of the economy occurs outside of the social structure, and no part of society can be thought of as independent of the natural environment (Johansson, 2011). In contrast, the representation of ‘Weak Sustainability’ recognizes that the three objectives generally must be evaluated independently because the correlation between the objectives is too complex to model in many cases and that tradeoffs between them must be considered. Although ‘Weak Sustainability’ is more widely considered, it is important to note the applicability of ‘Strong Sustainability’ to explaining the interdependence of the three areas.

Sustainability assessments of infrastructure have been growing since the 1990’s and started in the building sector before expanding into the transportation sector. A review of many tools available to rate the sustainability of transportation infrastructure can be found in Brodie et al. (2013), Clevenger et al. (2013) and Gudmundsson et al. (2013). Generally, sustainability rating tools within infrastructure are designed to determine sub-processes that occur throughout the infrastructure life and then identify and encourage practices or policies that contribute to the sustainability of the individual sub-processes. For example, the Greenroads rating system identifies the attributes of a road project that can contribute to sustainability, and then it defines sustainability best practices for these attributes (Muench et al., 2011). A second approach, which is less prevalent, is to define measures that contribute to sustainability and then to evaluate the infrastructure as a single system and determine the contribution to more sustainable outcomes. This second approach has been taken by the BE^{2}ST-in-Highways system (Lee et al., 2011).

An important aspect of sustainability is that a systems based framework should be employed within sustainability assessment in an effort to gain a thorough understanding of the broad impact of decisions, and how these impacts affect surrounding systems. This type of systems based framework is demonstrated in the Envision rating system developed by the Institute for Sustainable Infrastructure. A description of the Envision system can be found in Shivakumar et al. (2014) and Behr (2014). One module within the Envision rating system is focused on pathway contribution, which is a measure of the influence of the infrastructure project on the goals and vulnerabilities of the community in which the project is constructed. This approach to evaluating sustainability using a systems based perspective is highlighted in the methods presented in later sections of this paper.

2.2. Pavement Sustainability Assessment

As mentioned before, the assessment of pavement sustainability is narrower than an assessment of road sustainability because the system boundaries are smaller for a paving activity than for a road building activity. For example, road alignment can have an impact on sustainable outcomes for communities by avoiding certain environmentally or socially sensitive areas, but alignment is not a consideration for paving activities. Still, several attempts have been made to extract concepts from road sustainability for use in pavement sustainability assessment, some of which are described in more detail in the following sections.

2.2.1. Greenpave

Greenpave is a sustainability rating system developed by the Ontario Ministry of Transportation that defines specific strategies that contribute to the increased sustainability of pavements (Lane et al., 2014). The strategies defined in Greenpave are linked to 14 objectives that are seen as practical goals for increased pavement sustainability: long life pavements, permeable pavements, noise mitigation, cool pavements, recycled content, undisturbed pavement structure, local materials, construction quality, reduce energy consumption, GHG reduction, pavement smoothness, pollution reduction, innovation in design, and exemplary process. The strategies and goals were based on other sustainability assessment tools and the conclusions of a sustainable pavement workshop, which brought together stakeholders to discuss techniques and policies that can contribute to pavement sustainability (Chan, 2010).

In order to score a pavement project in Greenpave, the pavement characteristics are compared against predefined criteria in each of the 14 objectives. For example, it is expected that rigid pavements (i.e., those constructed using portland cement concrete) will last longer than other pavement types; thus, rigid pavements receive three points related to the long life pavement objective. The long life pavement objective is tied to the goals of reducing the impact of frequent rehabilitation, reducing life cycle emissions and reducing life cycle energy consumption (Lane et al., 2014). Therefore, the points earned in this case are predicated on the idea that rigid pavements have lower life cycle energy consumption and emissions values than comparable flexible or composite pavements; however, this assumption does not hold true in many cases (Xu et al., 2015).

2.2.2. FHWA's INVEST Pavement Scorecard

The US Federal Highway Administration (FHWA) has developed the web-based sustainability assessment tool: INVEST (Infrastructure Voluntary Evaluation Sustainability Tool) (FHWA, 2014). INVEST defines sustainability in terms of the triple bottom line, and it encourages balancing social, environmental and economic criteria (Brodie et al., 2013). Scoring with INVEST is completed within specific modules: System Planning, Project Development, and Operations and Maintenance. The total score, however, is not an aggregated value from the three modules. Instead, the modules are designed to serve as sustainability evaluations for different processes of the design, construction and maintenance phases (VanZerr et al., 2012).

Although the INVEST tool is designed to evaluate the sustainability of a road project, it has a dedicated scorecard specific to paving activities. The scorecard for pavements contains specific actions or goals that must be met in order to obtain a certain number of points (e.g., the use of life cycle cost analysis (LCCA) is awarded three points). Once the project is scored across all of the criteria, the sum of the scores is used to rate the project. The criteria specific to paving are (Bevan et al., 2012): LCCA, highway and traffic safety, educational outreach, tracking environmental commitments, reduce and reuse materials, recycle materials, long-life pavement design, reduced energy and emissions in pavement materials, contractor warranty, construction equipment emissions reduction, construction quality control plan, and construction waste management.

2.2.3. GreenLITES

GreenLITES (Green Leadership in Transportation Environmental Sustainability) is a sustainability rating tool that was developed for use by the New York Department of Transportation (NYDOT, 2014). GreenLITES was not specifically developed for paving activities, but every project conducted by NYDOT is evaluated using the GreenLITES framework, including projects that are not required to submit formal plans (e.g., pavement maintenance and bridge painting) (Eisenman, 2012). GreenLITES is a point-based rating system with five point categories: sustainable sites, water quality, material and resources, energy and atmosphere, and innovation (Clevenger et al., 2013). There are 175 points possible across the five categories, and projects are awarded a certification level based on the total points they receive. Specific activities that are not applicable to a large subset of the point criteria, such as pavement maintenance, can be certified by accruing sufficient points in a limited set of applicable criteria.

GreenLITES rating is based on the NYDOT's sustainability mission, which is modelled similar to the definition of sustainability put forth by the Brundtland report (McVoy et al., 2010). Following this definition, NYDOT set goals to: protect and enhance the environment, conserve energy and natural resources, preserve or enhance the historic, scenic, and aesthetic project setting characteristics, encourage public involvement in the transportation planning process, integrate smart growth and other sound land-use practices, and encourage new and innovative approaches to sustainable design, and how they operate and maintain facilities. GreenLITES was developed primarily as an internal monitoring and assessment system (McVoy et al., 2010).

2.2.4. BE^{2}ST-in-Highways

BE^{2}ST-in-Highways (Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways) was developed by the Recycled Materials Resource Center (RMRC) as a sustainability rating tool with the objective of quantifying the impact of using recycled materials in construction (Lee et al., 2011). The structure of BE^{2}ST-in-Highways includes two layers, a mandatory screening layer and a judgement layer (Lee et al., 2013). The screening layer is the first evaluation and is used to ensure that the project conforms to all regulatory standards. The judgment layer includes the calculation of nine metrics related to environmental and economic assessments: greenhouse gas emission, energy use, waste reduction (by including ex situ materials), waste reduction (by recycling in situ materials), water consumption, social carbon cost saving (economic benefits associated with mitigation of climate change), life cycle cost, traffic noise, and hazardous waste. The calculations for the judgment layer are performed using the tool Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) for LCA, FHWA's Realcost program for LCCA and the TNM-LookUp table developed by the US FHWA to evaluate noise reduction (Lee et al., 2011). The metrics are each weighted on a 0 to 1 scale to represent their degree of achievement towards goal targets.

Scoring a pavement project using the BE^{2}ST-in-Highways system is a two-step procedure. First, the criteria in the mandatory screening layer must be met; no points are awarded in this step. Secondly, the relative improvement of the project as compared to a reference project is evaluated across the nine metrics. The tool defines targets and points are awarded based on the achievement of these targets. For example, a twenty percent reduction in greenhouse gas emissions in comparison to a reference project is awarded two points. Of the reviewed pavement sustainability assessment tools, BE^{2}ST-in-Highways is the only tool that scores a project based on measurable outcomes of the project from a systems perspective, as opposed to scoring a project based on the individual components of the pavement system.

2.2.5. Additional Transportation Sustainability Assessment Tools

Several additional sustainability rating tools were not discussed in the previous sections, such as the HTMA Sustainable Highway Maintenance Tool (HTMA, 2014) or the Transportation Association of Canada Green Guide for Roads (Royal Roads University, 2014). In general, these sustainability assessment tools are designed for road sustainability, although some may be used in sustainability assessment regarding pavements. Furthermore, the structure and framework of these tools are similar to the rating systems that were described, even though they may maintain goals and audiences specific to the individual tool.

2.3. Discussion of Current Pavement Sustainability Assessment Tools

The benefit of each of the previously described sustainability assessment tools is that they are accompanied by clear action steps relating to the sustainability objectives outlined in the tool and these actions can be implemented in the design and construction of pavements. The structure of the rating tools that were reviewed, along with many others not detailed in this paper, is a guided framework to promote activities that are expected to result in more sustainable pavements, which is beneficial to informing decision makers of sustainable practices (Johansson, 2011). With the exception of the BE^{2}ST-in-Highways system, pavement sustainability assessment tools do not measure resulting changes in environmental, social or economic burdens from a systems perspective. Yet, although the BE^{2}ST-in-Highways system measures outcomes from a systems perspective, the criteria that it deems to contribute to sustainability are limited and are mainly environmental indicators. The remainder of the tools are designed on the fundamental assumption that implementing best practices represents progress towards more sustainable pavements; however, there is little regard given to the system outcomes or the potential interactions or co-linearity between the impacts of carrying out actions collectively.

Each of the sustainability assessment tools described previously connects practices that are designed to represent improvements in sustainability to related goals. If practices are planned or completed, points are awarded suggesting progress toward achieving the sustainability goal. The implementation of practices effectively becomes an indicator for sustainable performance. This process is problematic because practices may not be evaluated collectively, which has several implications including developing assessments where some goals become implicitly more important than others by potentially considerable margins. In other words, the set of actions taken (e.g., increased recycling or decreased asphalt mixing temperature) will affect each project to a different and unique extent. Without evaluating outcomes, the contribution of each action towards a specific objective or goal is unknown. Additionally, there is an assumption that actions equate to outcomes.

Bossel (1999) explains the limitations of measuring the progress towards sustainability using a set of indicators that is developed in an *ad hoc* manner without consideration of the systems perspective, which is the case with the majority of pavement sustainability assessment tools. To describe these shortcomings, Bossel (1999) stated,

> "…these lists must be criticized on several counts: (1) they are derived ad hoc, without a systems theoretical framework to reflect the operation and viability of the total system; (2) they always reflect the specific expertise and research interest of their authors; (3) as a consequence of (1) and (2), they are overly dense in some areas (multiple indicators for essentially the same concern), and sparse or even empty in other important areas. In other words, they are not a systematic and complete reflection of the total system, i.e., human society in interaction with its natural environment" (p. 12).

This helps to explain how some goals can be over emphasized.

As an example of the limitations of ad hoc evaluation, all of the tools that have been explored in this paper include the increased use of recycled materials as an indicator towards more sustainable road pavements. The main reasons for increasing recycled materials in pavements are: reduced environmental impacts, reduced costs, reduced amount of virgin materials used (i.e. conservation of resources), and reduced waste materials that require disposal, which also results in reduced land take. Using this practice as an indicator, increased use of recycled materials is a policy that may have various different benefits that address sustainable outcomes. Conversely, as presented in Ventura et al. (2008), increased recycled material in a pavement can potentially also negatively impact other indicators such as increase greenhouse gas emissions; thus defining the increased use of recycled materials as an increase in sustainability neglects the complex systems interaction that exists between the many indicators of sustainability (see section 4.2 for an example). Therefore, as opposed to a collection of individual indicators, sustainability should be measured by a net reduction in environmental or economic impacts or an overall improvement in quality of life.

Use of the results of environmental LCA within a sustainability rating tool can address a number of outcomes, or environmental impact categories. However, they generally do not include all environmental impacts (e.g., noise) and social impacts only indirectly (e.g., human health impacts resulting from environmental degradation, for instance from depletion of the ozone layer) or not at all (e.g., employment). While pavement LCA and LCCA has developed in recent years, there are still significant limitations in its application, particularly across the full life-cycle (Jorgensen et al. (2010), Santero et al (2011), Galatioto et al. (2015)) or in transparency and comparability (Glass et al. (2013)).

Furthermore, the shortcomings of indicators used in current tools to address outcomes can be highlighted by applying the DPSIR (driver, pressure, state, impact, response) framework used by the European Environmental Agency to understand the relationships between the environment and socio-economic activities (EEA 2007). In the DPSIR framework, the economic and social needs for a pavement can be represented as Drivers and the pavement construction creates Pressures on the natural environment, ultimately leading to a change in the State of the environment. The changed

State has Impacts on the surrounding systems and elicits a societal Response to mitigate the impacts. The Response may address the Drivers, or the resulting Pressures, State, or Impacts directly (Figure 1). This is representative of how the response may have greater influence on the system although it is designed for the purpose of addressing the impact. This framework for environmental impacts is described in Smeets and Weterings (1999) and OECD (2003) among other sources.

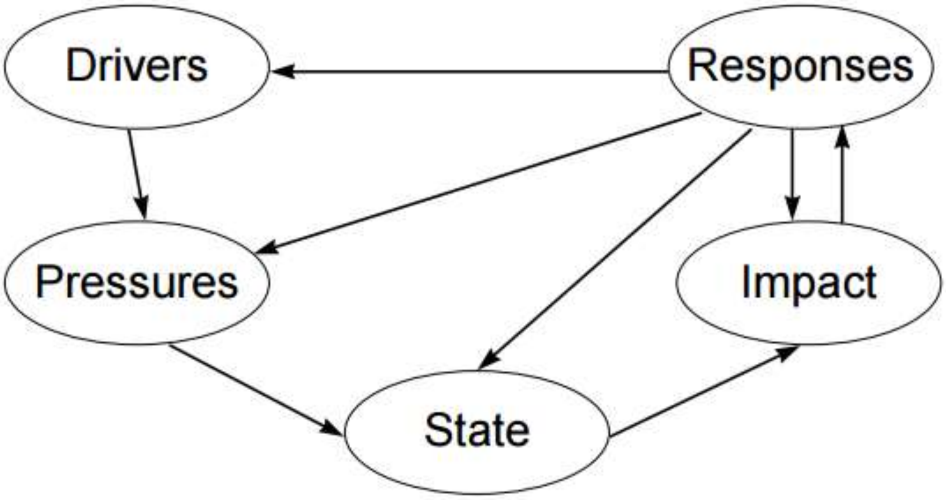

Figure 1 The DPSIR framework showing the relationship between socio-economic activities and the environment through a simplified causal interaction (Smeets and Weterings, 1999).

The majority of actions defined in pavement sustainability assessment tools are Responses that are designed to reduce the Pressure that the pavement system generates on the natural environment, society and economic budgets in order to produce a more sustainable state with fewer undesirable Impacts. As opposed to evaluating the Impact that results from sustainable Responses (e.g., measuring the reduction in global warming potential), modern pavement sustainability assessment tools treat the implementation of the Responses as the indicator for sustainability. This implies that the relationships between the Responses to individual Pressures and the changes in the State of surrounding systems (e.g., the natural environment), or the Impacts of this change in state is monotonic, which, given the highly complex nature of the interactions between the various systems where pressure is applied, may not be a reliable assumption.

Continuing with the DPSIR framework, one example of developing Responses to address a Pressure is the US legislation in 1991 that mandated the use of tire rubber in all new paving projects that received federal funding by 1994 (Amirkhanian, 1993). The legislation was a Response to the Pressure generated by large amounts of waste tires stockpiled across the US creating a negative Impact on the natural environment (Eldin & Piekarski, 1993). This legislation, however, was expected to increase costs of the pavement projects (Amirkhanian, 1993), which would have a significant effect on economic budgets. Legislation requiring the use of tire rubber in pavements is a simple example of why the outcomes of practices for sustainable pavements should be viewed as a system as opposed to addressing individual components of the pavement. As stated in Fiskel (2006), “Integrated assessment of sustainable systems cannot be accomplished by simply linking together a collection of domain specific models" (p. 17). In order to assess the sustainability of pavements, the unexpected Pressures or Impacts resulting from seemingly unrelated Responses must be assessed. A pavement should only be considered more sustainable if the total system shows a reduction in negative pressures or negative impacts to external systems, relative to common practice.

Finally, defining the system boundary is an essential step in an LCA study that helps to define the study scope but also assists interpretation of the results by acknowledging what processes or environmental impacts lie outside the study. Similarly, defining the 'total system' considered in a broader sustainability assessment is an important step for the same reasons but in some pavement sustainability rating tools, this step is missing, leaving the impression that the system is defined by the indicators or metrics, rather than the other way around. Limitations are not acknowledged and assumptions are not considered or declared.

3. Approaching a Systems View through Performance Management

This section presents an approach to viewing sustainability assessment from a more systematic perspective, as well as a method for linking sustainability assessment to an agency's performance management practices. Focusing on the system lends itself to the application of performance management; the ongoing and systematic approach to improving outcomes by using evidence-based decision making, continuous learning, and emphasizing accountability for performance. By adopting a performance management approach, the Impacts of Responses towards sustainability objectives may be evaluated.

Figure 2 integrates the DPSIR framework within a performance management framework and establishes an evaluation process for responsive actions that is based on sustainability objectives. The ellipses represent the established DPSIR framework (from Figure 1) and the shaded shapes represent the performance management framework. A critical component of the performance management framework is identifying strategic Goals and specific Objectives, which should then be used to guide actions. In this case, the actions align with the Responses from the DPSIR framework; therefore, the Responses to environmental impacts should react to sustainability Objectives and not directly to the environmental stimuli. To achieve this, the performance management cycle identifies Performance Indicators to evaluate the Response and its ability to meet a performance target or other criteria regarding the associated Impact. The evaluation is conducted using data collected about the Impacts and the results are assessed against the Objectives and used to adjust the Response. The iterative process developed by integrating the DPSIR and performance management frameworks can evaluate and adjust a Response to undesirable environmental Impacts based on sustainability Objectives and therefore helps to assess the outcomes of the system. Furthermore, the demonstrated approach links performance Targets directly to Responses and hence the State of the environment or its Impacts, providing clarity in Target setting.

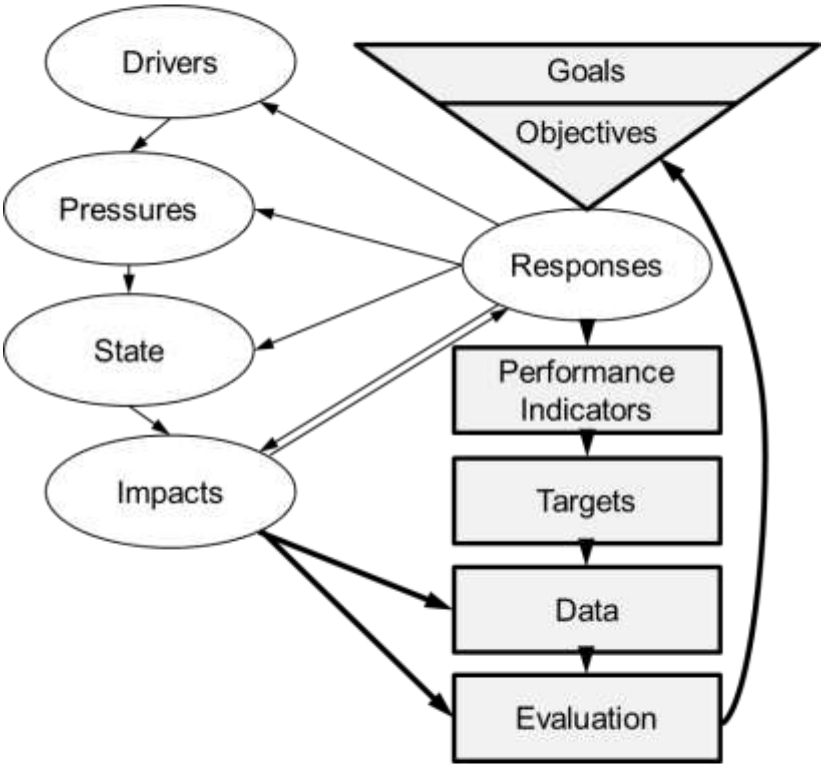

Figure 2 The DPSIR framework within a performance management framework to evaluate system outcomes

As discussed in the previous section, the DPSIR model is a system-level framework for considering environmental impacts that can help explain the interaction between system inputs – in the form of Drivers, Pressures and environmental States – and project-level outcomes/impacts and practices/responses. According to the DPSIR framework, the Response is determined based on the Impact observed, or the outcome. The Response is the practice or strategy for addressing the Impact, which is a result of the Drivers, Pressures and the environmental State. In this application, the Response should be assessed for its ability to address Impacts to meet the sustainability policy objectives. Many assessment tools use the Response in and of itself as the measure of sustainability as opposed to measuring its effect on the Impact. The framework in Figure 2 also helps illustrate that the Responses and the Indicators are not one and the same. The framework outlines that assessments should create Performance Indicators with Targets, use data to evaluate the Impacts in relation to the sustainability objectives, and then use this information to inform the pavement construction and management strategies. This application creates a performance management cycle integrated with the DPSIR model and provides a system framework to understand sustainability outcomes of project outputs. Incorporating performance management draws connections between inputs, outputs and outcomes by following the implementation of a strategy to evaluate performance in an iterative fashion and then managing the strategy based on the results.

3.1. Demonstrating Sustainability Assessment Based on Performance Management

The example in Figure 3 demonstrates an aspect of a sustainability assessment based on the performance management framework shown in Figure 2. The Goal is a high-level aim such as preserving the natural environment. The Objective follows and should be achievable and actionable. For example, the Objective in Figure 3 is to conserve resources, and one Response to address this Objective is to use recycled material in pavement construction and maintenance. Performance Indicators reflect the Goals and Objectives and are preferably outcomes-oriented. For example, it is useful to know the percent of recycled material used to meet the Objective; however, we want to examine the outcomes of this Response, which is why the DPSIR framework is adopted. Some Performance indicators for this case are energy consumption and GHG emissions from production and transport of materials, virgin material use and waste diverted from landfills (to preserve land resources) etc., perhaps with further indicators from evidence based assessments such as consequential LCA to assess changes from current practice. These Performance Indicators, when measured for a given project, provide information on outcomes and towards achieving the Objectives and Goals. The evaluation of these indicators starts by setting Targets that may be based on models, estimates, or past evidence. For example, the Target may be a maximum level of virgin material or a percentage decrease in GHG emissions from material production. Finally, the measured results, based on data acquired about the impacts, reflect outcomes that directly related to the Objectives.

The chosen Response (to increase the use of recycled materials), if successful, will change the quality or State of the environment and available resources, and slow resource depletion, perhaps the most obvious of the Impacts of the Pressure exerted by resource use. The Performance Indicators will provide the evidence for this, although considering the broader system and potential Impacts might identify where further evidence and Performance Indicators may be required. These might include biodiversity measurements; although it may be decided that this is outside the scope of the Objective stated here, it is likely to be within the scope of overall Goal. Identified Impacts outside the scope of any Goals and Objectives should be recognized and acknowledged. While the Response chosen for this example will mitigate the identified Pressure, a wider set of resources (e.g. fuels) should be considered in a systematic approach. Finally, the Response will not affect the Driver, which is a result of socio-economic demands that require transport policy responses, beyond those of pavement construction (e.g. demand management or alternative transport systems).

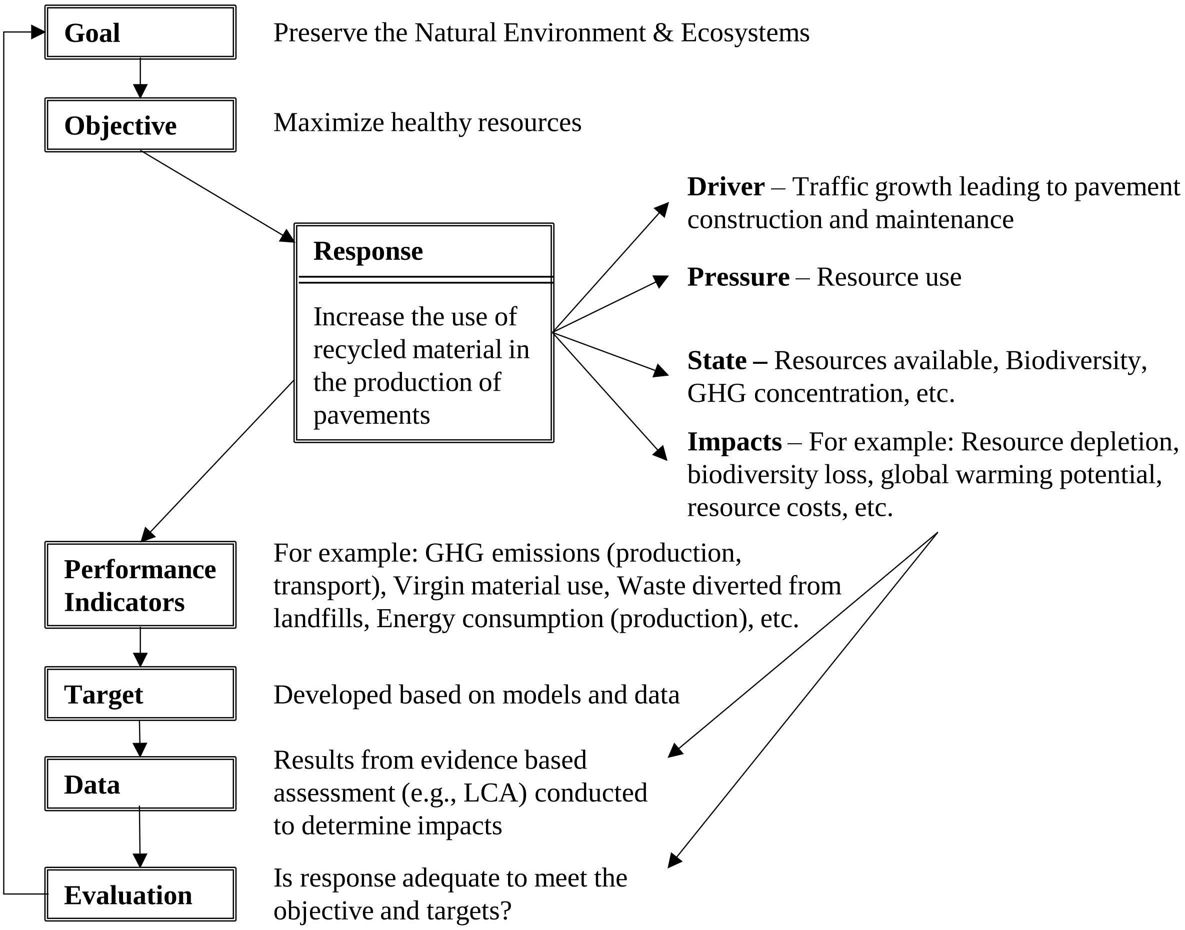

Figure 3 Example Application of Applying the Framework Shown in Figure 2

4. Defining Indicators of Sustainable Improvements in Pavements

The relationship between inputs, outputs and outcomes is important to understand in order to address how outcomes can be evaluated by sustainability assessments. Inputs are resources used to accomplish work (including money, people, materials, influence, knowledge, etc.). The work that is accomplished, which results in products or services is referred to as outputs. Finally, outcomes are the impacts of the work accomplished (i.e. outputs) on end users (Baird and Stammer 2000). The ability to measure outcomes relies on attributing them to outputs or other actions. As was discussed previously, sustainability assessments are often not measuring outcomes; rather they are using Responses to Impacts as proxies for outcomes, assuming that implementation of these Responses will result in more sustainable outcomes. The evaluation of sustainable outcomes requires indicators, or metrics, that measure performance outcomes that correspond to desired objectives.

To connect objectives of enhanced sustainability to Performance Indicators, a three tiered objective hierarchy framework was developed (fundamental objective with two levels of means objectives) that represents the strategic objectives (Figure 4). These objectives can then be used to guide road pavement projects and their use of materials and technologies to promote the strategic sustainability objectives. The objective hierarchy framework sets maximizing sustainability as the fundamental objective and the objectives leading towards maximizing sustainability are defined with a top down approach. Youker and Brown (2001) discuss the use of this type of objective hierarchy to answer specific questions regarding the achievement of goals. Given that sustainability assessment tools for pavements are ultimately designed to enhance the decision-making process, a process similar to that defined by Keeney (2007) was followed to develop an objective hierarchy. It is important to note that systems designed for different purposes will have different hierarchies of objectives. For the case of pavements, no decision is made about the geometry of the road; therefore the preservation of ecosystems is associated with a different set of means objectives than if the road as a whole were considered. The objective hierarchy is defined in Figure 4 and shows that the goal is to maximize positive impacts towards each objective at the base of the hierachy. The base-level objectives are derived from an aggregation of the objectives from the previously discussed sustainability assessment tools and the core set of indicators set by the Organisation for Economic Co-operation and Development (OECD, 2003). The base level of objectives reflect the means objectives, or objectives that are directly actionable. Achievement towards each of the means objectives can be measured using specific indicators.

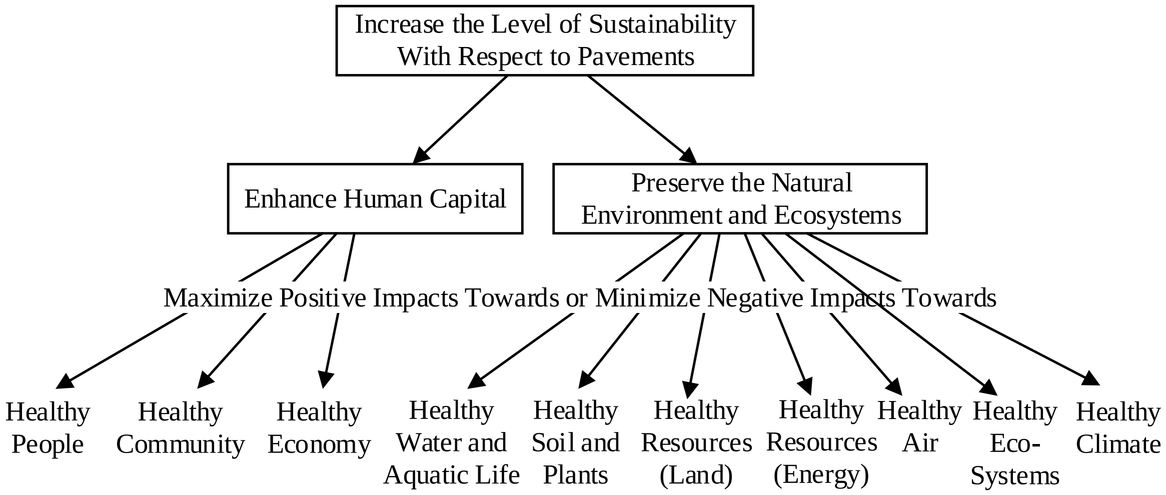

Figure 4 Goal/Objective Hierarchy for Enhancing the Sustainability of Pavements

Three important points must be discussed about the development of the goal and objective hierarchy as shown in Figure 4 and its implications. First, the analytical structure of any decision problem is dependant not only on the fundamental goal, but also, it is highly dependent on the values expressed by stakeholders. This is the rationale behind many agency-specific sustainability assessment tools. To overcome this, at least in part, the means objectives were defined thoroughly and broadly, accounting for the objectives revealed through the assessment tools that were reviewed. Secondly, as will be discussed in more detail in the following sections of this paper, the base-level means objectives occur over different time and spatial scales. Finally, the structure defined in Figure 4 deviates from the triple bottom line approach to sustainability and treats the economy as a process embedded with human capital, similar to the definition of strong sustainability as discussed in Adams

(2006) and Johansson (2011). Asking “why?” (as in Youker and Brown, 2001) can justify this positioning. Asking “Why is a healthy economy important?” may lead to an argument that a healthy economy can facilitate better environmental decisions; however, decisions about the economy are ultimately embedded within the human/social context. In other words, the natural environment is not reliant on the economy independent of human involvement, but human capital uses economic tools to develop the infrastructure through which it interacts with the natural environment.

4.1. Categorizing Impacts of Current Pavement Sustainability Assessment Tools

After defining an objective hierarchy, the next step is to define indicators to measure achievement towards the goals. Ideally, each of the means objectives defined in Figure 4 would be processed further into more fundamental objectives (e.g., healthy water could be further defined as minimizing eutrophication, minimizing water use, etc.). This research however, leaves the means objectives defined more broadly and instead provides indicators that can be used to assess progress towards more sustainable pavements for the given means objectives. To do this, the indicators defined in the four sustainability rating tools discussed previously (Greenpave, BE2ST-in-Highways, FHWA’s INVEST paving scorecard, and Greenlites) were collected, and the sustainable transportation categories presented in Black (2004) were also considered. In order to define the indicators, all pavement activities including shoulder and base work, were assumed within the boundaries of the analysis. Earthwork such as leveling berms was not included.

Many of the sustainability rating tools do not define indicators explicitly, but instead, they define actions that are related to one or more impacts on the desired objectives. For example, assessment tools increase the sustainabilty score if a project implements *in-situ* recycling of the pavement. *In-situ* recycling of the pavement is linked to several benefits including, reduced lifecycle costs, reduced environmental impacts and reduced construction time, which is expected to reduce time lost for vehicles in construction queues (Yang et al., 2015, Giani et al., 2015, Santos et al., 2015). There are, however, more direct ways to evaluate impacts on the means objectives than through the implementation of related actions.

The indicators from each of the sustainability assessment tools were collected and added to a spreadsheet where they were categorized based on their impacts on the means objectives defined in Figure 4. Many of the indicators had primary impacts related to multiple objectives and were counted in each of the objectives that they impact. Then the impacts were arranged across three spatial scales, drawing upon standard practice in LCA impact assessment methods such as TRACI (Bare, 2011) and supported by literature showing that some mechanisms (e.g., global warming potential) have global effects, but other mechanisms (e.g., terrestrial acidification) have regionalized impacts (Huijbregts et al., 2013). Finally, unlike the process used in Greenpave, not all of the indicators could be linked to specific objectives, and therefore, all of the indicators defined in the sustainability assessment systems could not be categorized within the set of means objectives. This discontinuity between indicators and objectives highlights the need for an analytical assessment to address sustainable outcomes and its potential to support an approach to pavement sustainability that promotes best practices.

Best practices have a place in sustainability assessments. For example, many pavement sustainability assessment tools include an indicator relating to monitoring construction quality. This is because having a construction quality management plan is expected to increase the probability of a project meeting performance and cost goals, thus reducing the need for environmentally and economically costly repairs. In this way, a well-managed asset is not necessarily a more sustainable asset, but a well-managed asset can increase the probability that certain sustainability goals will be achieved. This research does not include monitoring quality management of projects, or other best practices as sustainability indicators, but it is recognised that such practices and activities may improve the overall delivery of the project resulting in indirect sustainable outcomes. However, there is no stated, direct link between quality management and sustainability objectives or outcomes in the tools and as a result, these indicators fall outside the framework developed here. To do so, the quality measure (e.g., initial roughness) would need to be linked to an outcome (i.e., reduced fuel consumption and hence resource use or GHG emissions).

Similar to how impacts can be arranged across spatial scales, impacts vary across time and can be organized across temporal scales as well. For example, construction noise occurs over a short time frame whereas climate change occurs over an extended time frame. Additionally, impacts may affect multiple objectives across multiple timescales. For example, indicators linked to healthy soils and plants for a relatively short timescale (e.g., terrestrial acidification that can be recoverable) may impact food growth in future generations, which has impacts on social objectives. Also, it is well established that climate change will have an impact on human health (Goedkoop et al., 2009), as well as significantly impact healthy communities by affecting food growth (Leclère et al., 2014) over a long timescale. Pavements are typically long-lived because they undergo progressive M&R rather than being entirely replaced, so their end-of-life is difficult to define. However, aligning the impacts with different timescales introduces substantial uncertainties. Fortunately, if all else is equal, it is not expected that a reduction in impacts over a short time frame will lead to negative outcomes in future objectives, thus, the indicators in this paper will not address temporal scales and will focus on spatial divisions.

The objectives of the pavement sustainability assessment tools were distilled into their most basic impacts, and with input from several impact assessment sources, they were used to generate Table 1. Indicators from the assessment tools were not included in Table 1 if they showed no direct impact or if an action evidenced no change towards fulfilling objectives. For example, it is noted in Eisenman (2012) that there is no evidence that simply conducting an LCA, which is awarded two points in the Greenroads system, will lead to a more environmentally-friendly final outcome. A similar statement can be made about LCCA or Environmental Review Processes when it is not required that the decision makers compare multiple alternatives in an attempt to improve the anticipated outcomes.

Still, several criteria in Table 1 can be calculated directly by using pavement LCA tools or impact assessment methodologies. The remaining indicators - LCCA, queueing analysis, community outreach, construction and traffic noise, crash risk reduction and runoff quality – are evaluated using other means. There are several standardized methods for LCCA and queuing analysis (e.g., Realcost (FHWA, 2004)). The US FHWA has released methods for noise related measurements (FHWA, 2015a) and crash risk reduction can be defined in terms of increased pavement friction, which is related to the expected number of crashes on a roadway (e.g., Hall et al., 2009). Runoff quality can be estimated using a number of widely available methods (FHWA, 2015b). Finally, although not currently measurable in quantitative terms, community education and community outreach can be assessed qualitatively, although this may not be true of their outcomes.

Table 1 Indicator Criteria Defined for Each Means Objective in Figure 4

	Means Objectives	Local Indicators	Regional Indicators	Global Indicators
Natural Environment and Ecosystems	**Healthy Water and Aquatic Life**	Eutrophication, Ecotoxicity, Water Consumption	Aquatic Acidification, Runoff Quality	Ozone Depletion
	Healthy Soil and Plants	Ecotoxicity	Terrestrial Acidification	Ozone Depletion
	Healthy Air	Ecotoxicity	Photochemical Ozone Creation Potential	Ozone Depletion
	Healthy Land Resources	Land Take	Mineral Resource Depletion	n/a
	Healthy Energy Resources	n/a	n/a	Non-renewable energy use
	Healthy Climate	n/a	n/a	Global Warming Potential
Human Capital	**Healthy People**	Human Health Criteria, Construction Noise, Traffic Noise	Crash Risk Reduction	n/a
	Healthy Community	Time lost due to queuing at construction or maintenance	Community Education/Outreach	n/a
	Healthy Economy	Life Cycle Cost Analysis		n/a

n/a = not applicable

Within pavement LCA, output flows of pollutants are estimated, and then translated into impacts in terms of how the pollutants affect particular systems (i.e., mid-point indicators), or how the changes to the system ultimatley impact more fundamental objectives, such as impact on human health (i.e., end-point indicators). For a more thorough discussion on the differences in pollutant flows, mid-point inidcators and end-point indicators, see Goedkoop et al. (2009), among other sources. It is important to note that when environmental impacts are estimated through mid-point and end-point calculations, they can be broader than is presented in Table 1. For example, climate change can be linked to several ecosystem and human health concerns (Goedkoop et al., 2009). Another example is that energy resource depletion can lead towards more costly energy in the future. These two examples are indicative of the fact that no indicator can represent single objectives without also impacting other objectives. Finally, many of the environmental indicators and the land use calculations are explained in detail in impact assessment methodologies such as IMPACT 2002+ (Humbert et al., 2012) or ReCiPe (Goedkoop et al., 2009).

There are instances in Table 1 where objectives are limited to one or two spatial scales; these objectives are labeled “n/a” for scales that are not applicable. For example, the depletion of energy resources is not expected to have local or regional indicators because the impact is at the global scale, given that energy resources are traded on a global market.

Healthy Economy in Table 1 is defined by LCCA, but as discussed in Jorgensen et al. (2010), costing methods may not be the best approach for including economic impacts in sustainability assessments. The economy is a reactionary system, and the impacts of road construction on long-term economic outcomes are highly uncertain. Although it is true that the relationship between roads and economic prosperity has been evidenced in the literature (e.g., Bryceson et al., 2008), it is also anticipated that in the near future higher costs will be required to mitigate negative effects of global climate change, which are also directly impacted by the density of road infrastructure (Chinowskya et al., 2013). Therefore, minimizing LCCA results may not be the best approach to a healthy economy; however, in the absence of a more appropriate method for measuring healthy economic impacts, LCCA can provide useful information for decisions based (at least partly) on economic outcomes.

4.2. Linking to Sustainability Assessment

As previously discussed, it was found that the majority of pavement sustainability assessment methods recommend a set of best practices (Responses) that are expected to increase the level of sustainability of pavements. Generally, it is assumed that this will be achieved by improving the State of the environment in some respect(s) and hence reducing adverse Impacts (e.g., reducing GHG emissions and hence their concentration in the atmosphere, leading to reduced GWP and the projected Impacts on environmental and human health) although this is best done at a system level. Some practices, or Responses, may also be considered to reduce Pressure on the environment (e.g., by reducing land take through reduced use of materials) although the relationship between the Response and the Pressure in this case is unlikely to be simple. Few Responses suggested in pavement sustainability rating tools address Drivers but these are usually considered at a transport network or policy level (e.g., transport demand).

There may be several cases, however, where a practice that improves one component of the pavement system adversely affects other components of the system. As an example, we evaluate the case of a 10 cm mill and overlay on a 3.6 m wide lane that is 5 km long. The mix data and basic construction equipment details are shown in Table 2 and Table 3, respectively. The mix design from

Ventura et al. (2008) was used for two separate mixes: one mix contains 10 percent reclaimed asphalt pavement (RAP) where the aggregates must be transported 10 km to the plant and the mix 10 km to the site, and the other mix contains 20 percent RAP where the aggregates must be transported 10 km to the plant and the mix 89 km to the site. Assuming each pavement has an international roughness index after construction of less than 0.65, the first mix (10 percent RAP) will result in a pavement that is not rated as sustainable using the Greenpave procedure. The second mix (20 percent RAP) will be labelled Bronze using the Greenpave procedure. With all else equal, the mix with 20 percent RAP improves mineral resource depletion and land-take metrics by reducing material use and reducing the amount of waste materials needing disposal. Yet when an LCA was conducted using the ECO-comparator applied to Road Construction and Maintenance (ECORCE M; Dauvergne et al., 2014), it found that emissions, energy consumption and ecotoxicity values, among other criteria, were made significantly worse for the case rated Bronze by Greenpave (Table 4). Without an evaluation of how system Impacts are affecting the Objectives (see Figure 2), holistic sustainability is not captured by assessment tools and benchmarking or Target setting may not address the projected Outcomes. It is for this reason that applying a performance-based framework is proposed. By incorporating a feedback loop to evaluate the estimated Impacts in light of sustainability objectives, a systems approach is taken for sustainability assessment.

Table 2 General asphalt mix and tack coat design data

Asphalt Component Name	% by Weight for each mix	Assumed Density (kg/m^3)
Bitumen (Assume PG70-22 or Grade 50/70)	4.68/4.18	1250
RAP	10/20	1600
∑Aggregates	85/75	1520

Tack Coat Component Name	% Weight	Assumed Density (kg/m^3)
Bitumen	65.0	1250
Water Emulsion	34.4	1000
Acid	0.3	980
SBS Elastomer	0.3	1050

Table 3 Basic construction equipment details

Operation	Brand/Model of Equipment	Fuel Consumed (L/h)	Water Consumed (L/h)
Milling	Wirtgen W2100	94.0	1260.0
Sweeper	Bobcat S630	11.0	520.0
Tack Coat (Spray Truck)	Mack CHU613	16.0	0
Paver	Dynapac SD2550C	37.0	0
Breakdown Compactor (2)	Dynapac CP 142	14.0	15.0
Finishing Compactor	Dynapac CC324HF	14.0	15.0

Table 4 Limited LCA results for 10 percent and 20 percent RAP pavements

Pavement	Greenhouse Gas Emissions (kg eq.CO2)	Energy Consumption (MJ)	Chronic Ecotoxicity (kg eq. 1,4DCB)
10 Percent RAP	168,856	2,892,302	4,795,112
20 Percent RAP	191,823	3,167,500	5,094,924

5. Conclusions

The simplified example in the previous section highlights a need for an analytical framework to measure pavement sustainability. Although simplifications can be made in order to develop a list of best practices for more sustainable pavements or a set of metrics to detect progress towards sustainable pavements, assumptions should not be made regarding the overall state of the system and sustainable outcomes. Improved performance measured by some indicators may lead to poorer performance as measured by others; therefore, trade-offs should only be evaluated for the final state of the pavement. These systems trade-offs can begin to be made by weighting the performance indicators based on the most important outcomes with respect to stated objectives (similar to the BE^{2}ST-in-Highways system). Then the most sustainable solution can be defined as the one that best addresses the objectives as determined through the rating assessment.

The current state of pavement sustainability assessment tools relies mainly on best practices, which are expected to increase the sustainability of pavements (e.g., promoting recycling or long life roads). Although these practices are generally expected to reduce the environmental impacts or life cycle costs associated with a project, it should not be assumed that these practices will necessarily result in a more sustainable pavement. Pavements are engineered systems and changes in one component of a pavement design will influence several other aspects of the system. Based on this understanding, a systematic framework should be employed to measure the changes in sustainability outcomes resulting from decisions made regarding pavement design, construction and use.

A more systematic framework for assessing changes in pavement sustainability was presented in this paper in an effort to improve the current state of pavement sustainability assessment, as well as to link sustainability assessment to performance management. Sustainability tools that promote best practices are important to engineering design and management, but data-driven, performance-based assessments are useful to support and improve decision-making for sustainable outcomes. An agency that wishes to promote recycling as a way to reduce environmental impacts should attempt to estimate those environmental impacts rather than simply working on assumptions. Analytical approaches for sustainability assessments can be used alongside a best-practice-based approach to verify decisions made and promote pavement sustainability.

Pavements perform a critical role in the transportation sector, essentially connecting the movement of people and goods to the natural environment. Given the extent of pavements throughout developed countries and the development of sustainability science in recent years, it is clear that pavement sustainability plays a critical role in promoting more sustainable societies. The implementation of best practices for promoting more sustainable pavements can be improved by assessing their resulting outcomes using an analytical, decision-support tool, based on the methodology presented in this paper. This can greatly influence the environmental, economic and social impacts resulting from pavement construction and maintenance towards more sustainable outcomes.

6. Acknowledgments

The research presented in this paper was carried out as part of the Marie Curie Initial Training Network (ITN) action, FP7-PEOPLE-2013-ITN. This project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement number 607524.

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