Engineering 4 (2018) 200–208

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Sustainable Infrastructure—Article

A Project-Based Sustainability Rating Tool for Pavement Maintenance

Yibo Zhang *, J.P. Mohsen

Department of Civil and Environmental Engineering, University of Louisville, Louisville, KY 40208, USA

ARTICLE INFO

Article history:
Received 2 November 2017
Revised 5 December 2017
Accepted 8 January 2018
Available online 23 March 2018

Keywords:
Sustainability
Pavement maintenance
PSIM
Rating tool
Analytic hierarchy process

ABSTRACT

Pavements require maintenance to prevent undue distress or to restore performance; however, pavement maintenance and its impacts do not receive enough attention in many cases, and are either ignored or treated as a low priority. Most current maintenance activities have budget issues and only focus on removing deteriorated pavement sections. Deferred pavement maintenance has impacts on the environment and on society, and may thus affect the costs associated with maintenance. A sustainability rating tool is a good way to list, explain, and evaluate such impacts. Various sustainability rating tools have been developed for pavement; however, pavement maintenance has its own features that are different from those of the new construction, expansion, or reconstruction of pavements. This research project reviews nine sustainability rating tools for pavement, although none of these tools fully describe maintenance features or can be directly applied to evaluate maintenance projects. A new sustainability rating tool is then developed for pavement maintenance; this new tool can be used to evaluate individual projects and raise public awareness about the importance of pavement maintenance. Its details are described, and its use is demonstrated through an example to show the evaluation process and results.

1. Introduction

When addressing the problems that appear after pavements are built, some transportation agencies or pavement owners wait until the pavements fall into poor condition to take action, while others use preservation while the pavements are still in good condition. Both types of actions can be considered as maintenance, so maintenance activities can be divided into two parts: preservation, which is proactive; and reactive treatments.

Preservation, maintenance, and rehabilitation are terms that are commonly used to describe the activities that improve pavement performance and extend pavement life without increasing pavement capacity. Multiple resources indicate that preservation and minor or major rehabilitation can be seen as part of maintenance activities [1,2]; therefore, the term *maintenance* in this paper refers to any activity that can prevent, mitigate, or halt the pavement deterioration.

In traditional pavement maintenance, stakeholders encounter various problems that negatively affect either the maintenance process or the result.

First, the revenue available for pavement spending has fallen short since 2008 [3], and pavement maintenance is often treated as a low priority compared with other general pavement constructions. Therefore, most current pavement maintenance practices have tight budgets and are reactive treatments that only remove deteriorated sections of pavement. However, maintenance should not only be conducted to fix distress; it is preferable to look beneath deteriorating pavements to identify the actual cause of deterioration. Otherwise, although maintenance will restore pavement performance, it will not fix the initial cause of the distress, resulting in a need for repetitive maintenance. In the long run, expenditure on pavement operation and maintenance will gradually decrease if pavement performance can be maintained at a reasonable level.

Second, a pavement maintenance project affects the surrounding environment through, for example, energy consumption and emissions. Researchers commonly address the energy consumption and greenhouse gas emission of vehicles by developing high-efficiency engines or alternative fuels. However, within the transportation sector, pavement construction is a major consumer of energy and a significant source of emissions. In addition, many maintenance activities involve small-scale or short-term projects, such as pothole repair and crack sealing; however, the

* Corresponding author.
E-mail address: 1bo.speed@gmail.com (Y. Zhang).

https://doi.org/10.1016/j.eng.2018.03.001
2095-8099/

environmental impacts of smaller or shorter construction projects are likely to be ignored due to a lack of guidelines or onsite inspection.

Third, pavement transportation involves not only pavement and its ancillary facilities, but also the users and the neighborhood. It was reported that 3 545 693 miles (1 mile ≈ 1.6093 km) of pavement were built in the United States before 1960 [4]. Although some of this pavement has been rehabilitated or reconstructed, a large quantity has been in service for decades. The neighborhoods of these pavement sections have probably changed considerably over such a long-time period, and the needs of the neighborhoods are likely to have changed accordingly. In any case, pavement maintenance can offer better service, including improved safety and comfort, to users and neighborhoods by considering their specific needs.

In general, traditional pavement maintenance considers little more than the distresses affecting pavement and the techniques needed to fix these distresses. Sustainability, which reflects the needs of the economy, environment, and society, can be used to discuss the three categories of pavement-related problems mentioned above; thus, sustainable pavement maintenance is a good solution to minimize the abovementioned negative impacts and benefit the pavement maintenance industry.

2. The concept of sustainable pavement maintenance

The concept of sustainability was first introduced in the *Report of the World Commission on Environment and Development: Our Common Future* in 1987. The Brundtland Commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This initial definition only emphasized excessively broad needs, although both present and future were considered. Nevertheless, this definition was the start of sustainable development.

Sustainable pavement has become an emerging topic in recent years. Pavement maintenance is widely regarded to be a critical element of sustainable pavement; such maintenance involves the use of certain techniques that repair distresses and improve the performance of existing pavements, thus extending their service lives. In fact, it is commonly believed that pavement maintenance possesses intrinsic sustainability.

The Federal Highway Administration (FHWA) is an authority on pavement research and has been playing a leading role in promoting sustainable pavement and sustainable transportation in recent years at a national level, since it must consider situations in different regions in order to identify appropriate sustainable practices for the whole nation. In 2015, the FHWA [5] stated that sustainable pavement refers to "system characteristics that encompasses a pavement's ability to ① achieve the engineering goals for which it was constructed, ② preserve and (ideally) restore surrounding ecosystems, ③ use financial, human, and environmental resources economically, and ④ meet basic human needs such as health, safety, equity, employment, comfort, and happiness." This sentence goes beyond a definition of sustainable pavement; it involves different but related disciplines and provides four principles that should be followed for any pavement in order to make it sustainable.

There has been growing recognition that pavement maintenance has economic, environmental, and social impacts. In the same document mentioned above [5], the FHWA expressed its interest in studying the sustainability features of maintenance: One section of the document discusses the sustainable design of rehabilitation, and one chapter covers possible sustainable improvements of preservation and maintenance techniques. However, technique is just one part of a pavement maintenance project, and sustainable pavement maintenance should involve more than techniques.

Gransberg et al. [6] separated pavement preservation from pavement maintenance activities, and defined sustainability for preservation and maintenance as "promoting environmentally friendly practices that also provide technical and economic benefits." They discussed the environmental impacts of preservation and maintenance in terms of seven factors: virgin material usage, alternative material usage, program for pavement in-service monitoring and management, noise, air quality/emissions, water quality, and energy usage. Different preservation and maintenance treatments can therefore be recommended for projects based on the corresponding relationships among these seven factors, in addition to cost and technical features. No social impact from maintenance projects was considered.

To better determine the items that should be considered for a sustainable maintenance project, we first provide a clear definition of sustainable pavement maintenance.

Sustainable pavement maintenance covers more than traditional maintenance and encourages the whole project team to do more than repair distresses or restore pavement performance at particular sites. Sustainable pavement maintenance can be defined as a project-based collaboration that ① reasonably uses labor, money, and natural resources; ② reduces negative impacts on the surrounding environment; and ③ does not negatively affect the needs of pavement users, workers, and neighborhood people while restoring the pavement performance. In addition, it ④ should be considered as a component of the whole transportation system; ⑤ should comply with requirements at any level; and ⑥ should be perfected over time. Traditional maintenance repairs pavement structure, whereas sustainable maintenance improves the pavement system.

3. A literature review of existing sustainability rating tools for transportation or pavement

A sustainability evaluation is as important as a sustainability definition. The National Cooperative Highway Research Program (NCHRP), which was established under the Transportation Research Board (TRB), studies issues related to the planning, design, construction, operation, and maintenance of pavements in the United States. In a 2011 report, the NCHRP declared that "an assessment tool to properly quantify environmental sustainability in the pavement preservation and maintenance context is both missing and required" [7].

An exploration of the meaning and benefits of sustainable pavement maintenance only informs the industry that such maintenance is necessary and feasible; it is also necessary to consider how to measure the sustainability of pavement maintenance projects so that different projects can be comparable on a standard scale.

A rating (i.e., assessment) tool is able to serve the purpose of evaluation. In general, a rating tool has a list of every situation with sustainable features that a project or organization might encounter, and evaluates the project or organization performance under each situation. The project or organization then receives a score as an indication of its sustainability level.

The most popular rating tool for sustainable infrastructure is Leadership in Energy and Environmental Design (LEED®) from the US Green Building Council. Many sustainability rating tools for transportation or pavement have been inspired by the LEED® framework. The latest version of LEED® (v4) has five modules that can be used to evaluate different infrastructure construction. Neighborhood Development (ND) module [8], which is being used for new land development projects or redevelopment projects, contains certain credits related to pavement construction issues, such as the design and restoration of habitat or wetland and water bodies, and minimize site disturbance. In addition, LEED® Building Operations and Maintenance (O + M) module [9], which is designed for existing buildings that are undergoing improvement work or little to no construction, includes some material related to infrastructure maintenance, such as existing building commissioning, and occupant comfort survey. Both modules can thus be helpful for the consideration of sustainable pavement maintenance.

Various sustainability rating tools have been developed for pavement construction as well. In order to determine whether the existing rating tools adequately cover pavement maintenance activities, we review nine sustainability rating tools for transportation or pavement, as follows:

The latest version of Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) by the FHWA (version 1.2) has four modules, one of which is Operation and Maintenance (OM) [10]. The OM module evaluates the sustainability of an agency's operation and maintenance policies, processes, procedures and programs. In the OM module, 11 out of 14 indicators involve pavement maintenance; however, these indicators are designed to meet transportation agencies' needs. Thus, pavement maintenance is evaluated for its management and planning at the agency level rather than for related activities and impacts at the project level.

The Greenroads evaluation system is applicable to rehabilitation, preservation, and overlay projects. However, it can only be applied to maintenance construction projects that preserve the lives of roadways; it is not applicable to activities that are part of a site maintenance plan (usually performed by public agencies and their contractors). Some of its credits reflect maintenance and preservation activities and require related future plans. However, since Greenroads assumes that those future plans will be performed as promised, this rating tool cannot effectively monitor such activities in the long term [11]. In the latest version (version 2) of Greenroads, only 15 out of 61 indicators clearly involve maintenance; these occupy 11% of the total available points [12]. Most of the 15 indicators focus on construction activities. Greenroads can be applied to selected pavement maintenance projects; however, it ① limits the scope of maintenance, ② relies only on a plan to guarantee sustainability, and ③ discusses only the basic information regarding the maintenance activities.

Green Leadership in Transportation Environmental Sustainability (GreenLITES) has four tools [13,14] to incorporate sustainability into programs, projects, and practices. Although GreenLITES considers all pavement maintenance projects, whether such projects have plan sheets or only a proposal, only one indicator clearly mentions pavement maintenance.

Illinois—Livable and Sustainable Transportation Rating System and Guide (I-LAST) [15] provides project requirements under each category to make project sustainability measurable; it also provides practices that can result in sustainable outcomes at the project level. Within I-LAST, three out of 15 indicators clearly involve maintenance activities.

Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways (BE^2ST) can be used for highway projects during the planning and designing phase. One of its purposes is to encourage a wider adoption of recycled materials in roadway construction and rehabilitation; therefore, all of its indicators are restricted to issues related to quantifiable construction materials and processes [16]. Half of the 14 indicators in the judgement layer can be directly applied to rehabilitation projects, but none of the indicators involves preservation.

The design and pre-construction, construction, and post-construction of a pavement project can be evaluated by the Integrated VicRoads Environmental Sustainability Tool (INVEST) by VicRoads [17], and it can be applied to new construction, maintenance, or the reconstruction of pavement. However, only nine out of 48 indicators clearly consider the evaluation of pavement maintenance activities.

Sustainable Transportation Analysis and Rating System (STARS) considers the future use of a transportation project by evaluating transportation investments, rather than just evaluating the project's design and construction; thus, STARS incorporates the idea that "the use of a transportation project often has bigger impacts than its construction" [18–20]. Only three out of 21 indicators in STARS-Plan and one out of 12 indicators in STARS-Project are directly related to maintenance activities.

Sustainable Transport Appraisal Rating (STAR) [21] adds a fourth part to sustainability: the risk to the sustainability of a project's outcomes—that is, the risk that expected outcomes may not be realized or sustained. Only six out of 18 STAR indicators directly involve maintenance.

Green Pavement Design Rating System (GreenPave) focuses specifically on the pavement component and on pavement-related items [22] such as pavement structure, rehabilitation strategies, use of material, pavement performance, and type of vehicles and equipment used during construction, rather than focusing on the entire road. GreenPave can be applied at the design stage and the as-constructed stage of a project. Out of 14 GreenPave indicators, 11 are directly related to maintenance. Although GreenPave has declared that it can be used for new construction and rehabilitation projects, none of the indicators reflect the need for preservation and other maintenance projects.

In conclusion, compared with general pavement construction activities and existing sustainability rating tools for transportation or pavement, a number of content areas are substantially different for a project with a maintenance focus. The rating tools discussed above do have categories or indicators that directly consider pavement maintenance activities. However, these rating tools do not focus on maintenance activities as much as on design and new construction throughout the life-cycle of transportation infrastructure, which limits their applicability to quantifying the sustainability of maintenance activities.

The literature review in this section also demonstrates the reasonability of NCHRP's suggestion that a sustainability rating tool exclusively designed for pavement maintenance is needed. Such a tool is necessary, both to supplement the theory of sustainable pavements and to benefit the pavement maintenance industry.

4. Development of the Pavement Sustainability Index for Maintenance

Our new rating tool, called the Pavement Sustainability Index for Maintenance (PSIM), evaluates the sustainability of pavement maintenance projects. This tool will cover items that are related to the impacts under the triple bottom line (TBL, which refers to economy, environment, and society). The purposes of PSIM are to:

- Provide a bridge between the concept and practice of sustainable pavement maintenance;
- List and define sustainable and practical solutions in the pavement maintenance industry;
- Reasonably evaluate and quantify the sustainability of individual pavement maintenance projects;
- Provide an index for users to conveniently look up sustainability activities and compare the sustainability of different activities or projects;

- Establish an award certification according to the level of sustainability achieved;
- Track and quantify sustainability goals over time;
- Involve all stakeholders as early as possible in a pavement maintenance project; and
- Raise public awareness about making maintenance activities sustainable.

PSIM was developed through the following five steps:

- Determine the rating categories;
- Determine the rating indicators under each category;
- Determine the priority of each category;
- Determine the points under each indicator; and
- Determine the certification level.

4.1. Determination of rating categories

The first step to develop a sustainability rating tool is to determine the rating categories. Each category focuses on certain sustainability indicators. Table 1 shows the categories that were determined for PSIM.

The eight categories determined for PSIM are described below:

- *Management* (Mn) reflects how a pavement maintenance project should be a system—not only at the project level, but also as a part of the whole pavement system.
- *Technique* (T) incorporates the sustainability topics associated with pavement maintenance techniques.
- *Material* (Mt) is always one of the top concerns of sustainable infrastructure, because materials take a great deal of energy to produce, transport, store, and dispose of, and because materials themselves are precious resources.
- *Energy and water* (EW) considers energy conservation and emissions reduction when using electricity and fuel, and considers the protection of water resources.
- *Environment* (E) directly deals with any kind of pollution to the environment or harmful effects on people resulting from pavement maintenance activities, and attempts to remove the negative impacts of pavement maintenance activities on the surrounding natural environment and on the community as much as possible.
- *Safety* (S) addresses the importance of safety during a pavement maintenance project for pavement users, the working crew, and people living or working in nearby communities.
- *Community* (C) focuses on the community near the pavement maintenance project, which includes the people living or working nearby, the cultural environment, and anyone who will benefit from the sustainable pavement maintenance project, whether directly or indirectly.
- *Innovation* (I) evaluates creative and practical ideas to improve the sustainability of pavement maintenance, and recommends the incorporation of experience from other sustainable projects into pavement maintenance.

4.2. Determination of sustainability indicators

Indicators enrich the details of the rating categories. Jeon and Amekudzi [23] reviewed 16 frameworks for sustainable transportation and listed 177 rating indicators to evaluate any sustainable progress in transportation. Litman [24] also performed comprehensive research on indicators for sustainable transport planning. In addition, we used the indicator distribution of the LEED® modules (i.e., ND and OM modules) and the nine rating tools for transportation or pavement discussed above as references in order to determine indicators for each category. The chosen indicators were carefully designed to avoid overlapping. The final list of sustainability indicators within each category for pavement maintenance is shown in Table 2.

Table 1
Rating categories of PSIM in a pavement maintenance project.

Input		Output	Others
Abstract inputs	Concrete inputs		
Management Technique	Material Energy and water	Environment Safety Community	Innovation

4.3. Determination of category priority

The analytic hierarchy process (AHP) was used to determine the weighting of each PSIM category. The AHP, which was developed by Thomas Saaty in the early 1970s, is a subjective method of ranking different elements and making decisions. The AHP has been accepted as an industry standard and is widely used in different fields [25,26]. It uses pairwise comparison to generate ratio data so that the result shows how much one item is prioritized over another, rather than providing a list in order of importance. The AHP first decomposes the decision problem into a hierarchy of a set of sub-problems, and then uses the judgement of professionals or stakeholders to establish the priority of each sub-problem; finally, it provides numerical weights for the whole hierarchy.

A representative group was invited to provide opinions on the priority of each category; the group included:

- Employees from transportation agencies and maintenance companies;
- Working crew members (including engineers and technicians);
- Teachers and students of civil engineering who were involved in at least one course related to sustainable design;
- Motorists, pedestrians, and bicyclists who have passed by pavement maintenance projects;
- Residents and workers in a community where the pavements have been maintained.

The group's opinions were processed by an AHP software named Expert Choice in order to calculate the priorities of the eight categories. The means of the individual results were then calculated and normalized to obtain the final priorities. The results (Table 3) showed that Safety (0.274) was ranked first followed by Management (0.148), Environment (0.139), Technique (0.109), Material (0.106), Community (0.099), Energy and water (0.080), and Innovation (0.045).

4.4. Determination of points distribution

Most of the existing sustainability rating tools for transportation or pavement distribute points under each indicator (also known as indicator weighting) by subjective judgement from the developers or users of that rating tool. PSIM will use a statistical approach as an objective weighting method to distribute points under each indicator.

First, the maximum possible points that can be earned from PSIM are set at 200. The possible points under each category were calculated in proportion according to the category priorities obtained earlier as shown in Table 3.

The points associated with each indicator were distributed by reviewing the practices of eight state departments of transportation (DOTs): California, Colorado, Florida, Minnesota, New York, Oregon, Washington, and Kentucky. These state DOTs are believed to have the best sustainability practices [27] or to effectively improve the sustainability of transportation infrastructure [28] across the United States.

Table 2
Rating indicators of PSIM.

Category	Indicator	Note
Management	Project team	Everything related to the project should be reported to the project team
	Budget plan	A budget plan is needed to determine and monitor project expenses
	Quality management	The procedure and performance quality of the project should be guaranteed for successful delivery
	Emergency dealing	Inappropriate reactions to unpredictable events will impair project efficiency
	Maintenance schedule	Maintenance activities should be implemented and finished in time, and performance monitoring should be planned ahead
	Project record	Information on previous and current maintenance activities should be conveniently retrievable
	Work zone management	The work zone should be well defined and managed with consideration for the needs of the working crew, traffic, and neighbors
	Crew training	The working crew should be aware of the construction procedure, equipment operation, performance requirements, and sustainability
	Project interaction	Communication must be conducted well to reduce conflict between different construction projects in the same area
Technique	Maintenance techniques	Reasons should be given if specific maintenance techniques are selected from multiple options
	Material production	The sustainability of the asphalt/concrete plant should be considered
	Distress analysis	Actual reasons leading to the distresses should be investigated and used as guide for maintenance
	Standard procedure	A standard maintenance procedure should be followed for consistent results
	Disturbance and repair	Any damage to the adjacent infrastructure should be repaired
	Smoothness adjustment	An appropriate approach should be implemented to remove obvious faulting between maintained and adjacent pavements
	Pavement uses	Pavements for different purposes should be maintained accordingly
	Weather adaption	Maintenance projects should be planned and implemented based on the weather and climate
	Preservation	Preservation prevents distresses and is believed to have intrinsic sustainable features
Material	Quality certification	The quality of the construction materials should be guaranteed
	Local materials	Construction materials should be obtained locally whenever possible
	Materials storage	Construction materials should be appropriately protected when stored onsite
	Recycle materials	Excessive or waste materials should be recycled whenever possible
	Alternative materials	Alternative materials are recommended if they can reasonably replace energy-intensive materials
	Earthwork	The cut-fill balance and the stockpile of soil should be carefully considered if subgrade work is involved
Energy and water	Efficient lighting	Renewable-energy and high-efficiency bulbs are recommended for construction and traffic lighting
	Energy consumption I: construction	The energy used by the construction equipment and the working crew onsite should be considered
	Energy consumption II: transport	The energy used to transport construction materials, equipment, and the working crew should be considered
	Energy consumption III: traffic	The energy used by vehicles in traffic should be considered
	Water consumption	The water used during the project should be considered
	Heat island alleviation	Methods of reducing the heat absorbed by or released from the asphalt pavement should be considered
Environment	Solid waste	The processing and transportation of solid construction wastes should be considered
	Stormwater and liquid waste	Liquid construction waste and contaminated stormwater should be considered
	Air quality	Pollutants emitted to the air should be considered
	Noise control	Appropriate methods should be considered to mitigate construction and traffic noise
	Vibration control	Maintenance activities resulting in noticeable vibration should be appropriately scheduled and minimized
	Night work	The scope and schedule of night work should be carefully determined
	Ecology conservation	The natural environment that is disturbed by maintenance activities should be restored and protected as much as possible
	Slope protection	Soil and rock on steep or long slopes should be stabilized or protected
	Shoulder protection	The pavement shoulder should be kept integral or well maintained
Safety	Traffic control	Appropriate and reasonable traffic control should be planned and implemented
	Construction safety	Safety issues affecting the working crew and construction equipment should be considered
	Roadway and roadside safety	Safety structures and devices for pavement users and neighbors should be considered
	Pedestrian and bicyclists	The needs of pedestrians and bicyclists should be considered
	Drainage	The drainage system should be protected or well maintained
	Snow/ice removal	The activities and materials involved in snow/ice removal should be considered
	Traffic marking	Traffic marking should be restored after being disturbed
	Glare control	Appropriate methods should be implemented to mitigate glare from construction lighting and vehicle headlights
Community	Road access I: users	Different pavement users should have convenient access to the infrastructure
	Road access II: infrastructure	The junction area between the pavement and other infrastructure requires additional consideration
	Landscape design	The aesthetic design and related safety issues of the adjacent vegetation should be considered
	Aesthetic design	The aesthetic design and related safety issues of adjacent human-made objects should be considered
	Culture conservation	Any cultural elements within the pavement system should be considered
	Stakeholders involvement	An effective channel should be established for stakeholders to express their opinions
	Notification	Basic information about the project should be delivered to stakeholders or any other interested people
	Ease of use	Any approach to improve the comfort of pavement users should be considered
	Community adaption	Maintenance activities should be planned and implemented by considering the characteristics of the neighborhood
	Sustainability promotion	The concept of sustainable pavement maintenance should be recommended to more people
Innovation	Creative ideas	Any creative techniques that can improve the sustainability of the pavement maintenance project should be considered
	Sustainability representative	It is recommended that an individual who is familiar with sustainable infrastructure be involved in the project
	Certified sustainable pavement	Extra points can be earned if the existing pavement was certified by a sustainable transportation/pavement program

Table 3
Points distribution under PSIM rating categories.

Category	Normalized priority	Points distribution
Management	0.148	29
Technique	0.109	22
Material	0.106	21
Energy and water	0.080	16
Environment	0.139	28
Safety	0.274	55
Community	0.099	20
Innovation	0.045	9
Total points		200

The procedure to determine the points under each indicator by reviewing state DOT practices is shown below.

(1) Collect the manuals related to pavement maintenance construction from the state DOT website.

(2) Review the manuals and determine which manuals/chapters/sections discuss PSIM indicators (over 300 manuals were collected and reviewed).

(3) List the manuals/chapters/sections as "practices" of the state DOT under the corresponding indicator. There are three levels in order to demonstrate the quantity of manuals/chapters/sections involved (Level 1: a few; Level 2: some; Level 3: many).

(4) Determine whether the "practices" are ready to be applied to pavement maintenance practices. This readiness will be demonstrated by three coefficients (3 points: ready; 2 points: somewhat ready; 1 point: not ready; 0: not discussed).

(5) Multiply the "level" by the "coefficient" to obtain the practice score of the state DOT (the score ranges from 0 to 9).

(6) The average practice score under each indicator that was calculated from the eight state DOTs' practices is then slightly modified based on how many sectors of the TBL the indicator involves.

(7) The modified practice score is the PSIM points under each indicator; the final results of the points distribution are shown in Table 4.

4.5. Determination of certification level

After a pavement maintenance project has been evaluated within the PSIM framework, a score called the Pavement Sustainability Index (PSI) will be awarded to the project to reflect its sustainability achievements.

The existing sustainability rating tools for pavement or transportation calculate the total points earned by projects or programs under each indicator as the basis for certification. However, for PSIM and pavement maintenance projects, it is possible that a pavement maintenance project will not cover all the indicators, since each project has a unique background and the scale of each project may vary considerably. Thus, the PSI should be a reflection of the evaluation under the relevant indicators by considering both the indicators covered and the points earned.

A typical PSI is a combination of two parts: the quantity of indicators involved, and the percentage of points earned under the involved indicators. For example, if the PSI of one project is 20/50%, it means that the project involves 20 PSIM indicators and has earned half of the maximum points that can be earned under those 20 indicators.

In order to demonstrate the sustainability achievements of different pavement maintenance projects, a reasonable certification level should be granted for a project after evaluation and PSI calculation. There are three certification levels based on the indicator quantity and the approximate scoring rate as shown in Table 5. One to three PSIM stars will be awarded to a project according to its PSI.

5. A demonstration of the evaluation process

In order to check the applicability of PSIM on an actual pavement maintenance project, a commonly conducted pavement maintenance activity in urban areas—that is, utility cut restoration—was selected as a case study to show the evaluation process. The primary function of the pavement system is for transportation; however, it also serves as corridors for infrastructure providing water, gas, electricity, sewers, and other utilities to businesses and residences. Performing installation, repair, or modification on these infrastructure systems often requires road cuts to access the buried assets, which adversely affects the life expectancy of the pavement. The typical contents of a PSIM evaluation report (i.e., the evaluation results) include the following:

- The actual and achievable PSI and the certification (if applicable);
- An indicator-by-indicator explanation;
- A list of strengths (sustainability achievements) and weaknesses (potential improvements); and
- Specification of the activities that deserve Innovation points (if applicable).

A utility cut restoration project on asphalt pavement at Fern Valley Road and Shepherdsville Road in Louisville, Kentucky was selected as the first case study. Louisville Water Company (LWC) scheduled a pavement digging due to a water main break in 17 June 2015, and asked the contractor to conduct asphalt pavement restoration due to the utility cut on the following day. The construction site was located on the northwest corner of the intersection of Fern Valley Road and Shepherdsville Road, where there is a large parking lot along the road. After the pavement was dug, the main break repaired, and the trench backfilled, a local contractor conducted a thin hot-mix asphalt (HMA) overlay of approximately 60 feet $\times$ 24 feet (1 feet = 0.3048 m) to restore the pavement cutting area on 18 June 2015, and finished the work on the same day. It was sunny on 18 June 2015, and there was a heavy rain at dusk on 19 June 2015.

Different resources were used to obtain information on the project, including daily work assignment reports from LWC, field visits, working crew interviews, communications (e-mails and periodic meetings) with the officials of LWC, and Google Maps. If the information required for a certain indicator was not available, a decision was made based on observations, or else no points were granted under that indicator.

The PSIM indicators involved in this project and their corresponding explanations are shown in Table 6.

This project earned a total of 37 points under 33 PSIM indicators; therefore, the project's PSI is 33/32.5%. This rating means that this pavement maintenance project was not sustainable, as defined by PSIM.

Based on the sustainability evaluation results, the strengths of this utility cut restoration project included a tight schedule, good traffic control, and reasonable parking of construction equipment; the weakness of the project were the collection and disposal of solid wastes, the provision of onsite notification about the finishing date, and air quality control.

Table 4
Points distribution of PSIM.

Category	Indicator	Average	Category priority	Initial points distribution	TBL sectors involved	Modified points distribution
Management	Project team	2.375	29	2	3	2
	Budget plan	2.875		3	2	2
	Quality management	5.125		5	3	5
	Emergency dealing	4.125		4	3	4
	Maintenance schedule	2.875		3	2	2
	Project record	5.125		5	3	5
	Work zone management	4.25		4	3	4
	Crew training	2.875		3	3	3
	Project interaction	2		2	3	2
Technique	Maintenance techniques	0.25	22	0	3	2
	Material production	1.5		2	3	2
	Distress analysis	2.75		3	3	3
	Standard procedure	7.875		10	3	6
	Disturbance and repair	1.625		2	3	2
	Smoothness adjustment	0.5		1	3	2
	Pavement uses	1.875		2	1	2
	Weather adaption	0.5		1	2	1
	Preservation	1.125		1	3	2
Material	Quality certification	7.875	21	8	1	5
	Local materials	1.25		1	2	2
	Materials storage	1.75		2	3	3
	Recycle materials	3		3	2	4
	Alternative materials	1.125		1	2	3
	Earthwork	4.5		5	2	4
Energy and water	Efficient lighting	3.25	16	6	2	4
	Energy consumption I: construction	3		6	2	4
	Energy consumption II: transport	1.5		3	2	3
	Energy consumption III: traffic	0		0	2	2
	Water consumption	0.75		1	2	2
	Heat island alleviation	0		0	1	1
Environment	Solid waste	4.75	28	4	2	4
	Stormwater and liquid waste	5.875		5	1	4
	Air quality	4.5		4	1	4
	Noise control	4		3	2	2
	Vibration control	1		1	2	2
	Night work	0.625		1	2	2
	Ecology conservation	6.375		5	2	5
	Slope protection	5.375		4	3	3
	Shoulder protection	2.125		2	3	2
Safety	Traffic control	8.25	55	12	3	10
	Construction safety	5.75		8	1	8
	Roadway and roadside safety	5.625		8	1	10
	Pedestrian and bicyclists	4.125		6	1	6
	Drainage	6.125		9	2	8
	Snow/ice removal	3.25		5	2	5
	Traffic marking	4.625		7	2	6
	Glare control	0.375		1	1	2
Community	Road access I: users	3.875	20	2	2	2
	Road access II: infrastructure	4.375		2	2	2
	Landscape design	7.25		4	2	4
	Aesthetic design	3.25		2	1	2
	Culture conservation	4.25		2	2	2
	Stakeholders involvement	4.625		3	2	3
	Notification	2.25		1	1	1
	Ease of use	2		1	1	1
	Community adaption	4.125		2	2	2
	Sustainability promotion	0.75		0	1	1
Innovation	Creative ideas	1.5	9	5	3	4
	Sustainability representative	1.25		4	3	3
	Certified sustainable pavement	0		0	3	2

Table 5
PSIM certification levels.

Approximate scoring rate	Quantity of indicators		
	20 to 29	30 to 39	40 to 60
0% to 40%	Not sustainable	★	★★
41% to 50%	★	★★	★★★
51% to 60%	★★	★★★	★★★ (also promoted as "demonstration project")

Table 6
PSIM evaluation results for a utility cut restoration project in Louisville, Kentucky.

Category	Indicator[a]	Maximum points	Actual points	Explanation
Management	Project team	2	2	People at the three utility agencies were designated to be in charge of utility cut restorations; they have relationships with contractors
	Budget plan	2	0	N/A
	Quality management	5	2	Both backfilling and pavement restoration were visually checked
	Emergency dealing	4	0	N/A
	Maintenance schedule	2	2	Tight schedule; digging started one day before pavement restoration; pavement was restored within one day and was completed before the rainfall
	Project record	5	2	Only the project log from LWC was available
	Work zone management	4	2	Equipment, vehicles, and tools were well organized at the nearby parking lot, but there were no guidelines about work zone management
	Crew training	3	1	An experienced working crew was working on site but did not know about sustainable pavement maintenance
Technique	Material production	2	0	HMA was used
	Standard procedure	6	1	Pavement restoration followed the standard procedure from contractor, but performed no trench backfilling. Louisville Metro is seeking standard procedures for trench backfilling, and the project is under progress at the time of this project
	Pavement uses	2	0	Asphalt pavement for different uses all followed the same restoration procedure
Material	Quality certification	5	0	N/A
	Local materials	2	0	N/A
	Materials storage	3	0	There was no protection for the construction materials
	Earthwork	4	0	Compaction of backfill was not observed
Energy and water	Energy consumption I: construction	4	0	Traditional construction equipment was used
	Energy consumption II: transport	3	1	Carpooling was observed
	Energy consumption III: traffic	2	2	Traffic speed was not decreased while passing the work zone
	Heat island alleviation	1	0	No such treatment was applied
Environment	Solid waste	4	1	The pavement surface and the shoulder between lanes and curb were clean, but not all of the asphalt waste was removed from the site. The destination of the wastes was unknown
	Air quality	4	0	N/A
	Noise control	2	0	N/A
	Vibration control	2	0	N/A
	Ecology conservation	5	2	Existing plants were not disturbed, but some asphalt mixture waste was left on the lawn alongside the pavement
Safety	Traffic control	10	8	This was well designed and effective. Traffic control was initiated before digging. Traffic cones were removed from the pavement after construction but were not removed from the site. No guideline for traffic control was observed
	Construction safety	8	4	There were no accidents, but the working crew did not wear reflective safety vests. No guideline for construction was observed
	Traffic marking	6	4	All traffic markings that were destroyed during construction were restored, but the source of the marking material was unknown
Community	Road access I: users	2	2	The project did not affect the people entering or exiting the parking lot
	Stakeholders involvement	3	1	LWC and the contractors were observed to be the stakeholders involved
	Notification	1	0	N/A
	Sustainability promotion	1	0	N/A
Innovation	Sustainability representative	3	0	N/A
	Certified sustainable pavement	2	0	N/A
Total points		114	37	
Percentage earned			32.5%	
Certification level			Not sustainable	

N/A: Information not available.
[a] This project includes 33 indicators.

6. Conclusions

The pavement infrastructure is a valuable asset to the nation, and a great deal of effort—including labor force, money, and other resources—is made every year to maintain the pavement system and serve its users. Sustainable pavement and sustainable transportation have gained more attention in recent years because people have realized that pavement construction has negative impacts on the surrounding environment and communities [29]. It is believed that sustainability will be a great solution for the modern pavement industry. There has been a potential consensus indicating that pavement maintenance possesses the intrinsic feature of sustainability because proper maintenance keeps pavements serviceable and extends their service life.

In this paper, pavement maintenance was examined with a focus on the pavement construction process in order to discuss its sustainability, and a descriptive definition of sustainable pavement maintenance was provided. To make different pavement maintenance projects comparable on the basis of sustainability, and to better promote the concept of sustainable pavement maintenance, a sustainability rating tool for pavement maintenance was developed in five steps. PSIM, the rating tool, has eight categories, 60 indicators, and 200 possible points to effectively evaluate the sustainability of any pavement maintenance project fixing distresses. Compared with existing rating tools, PSIM involves unique approaches to weigh each rating indicator and determine a certification level; pavement maintenance projects can earn certain points and certification if their PSI passes corresponding requirements.

A utility cut restoration project conducted in Louisville, Kentucky, was selected to demonstrate the PSIM evaluation process and results. The results indicated that PSIM was successfully applied to the pavement restoration project after the utility cut. Although the utility cut restoration project that was selected was not sustainable according to the PSIM evaluation, some suggestions were offered to improve the sustainability of similar pavement maintenance projects, including onsite disposal of solid waste, putting up a notification of the finishing date during construction, and dust control. Once these suggestions are adopted by similar projects in the future, these projects will receive a higher PSI, so that the sustainability of similar projects will be improved. PSIM reveals opportunities to improve the sustainability of pavement maintenance projects, including suggestions on what to consider and how.

In the future, more participants should be invited to be involved in the priority determination of the rating categories. It is also recommended that the performance of PSIM should be tested on various projects on a long-term basis; the PSIM framework can then be refined based on the application results.

Compliance with ethics guidelines

Yibo Zhang and J.P. Mohsen declare that they have no conflict of interest or financial conflicts to disclose.

References

[1] King AO. Maintenance and preservation: a definition [Internet]. Washington: Washington State County Road Administration Board; c2006 [cited 2015 Aug 20]. Available from: https://www.crab.wa.gov/LibraryData/RESEARCH_and_REFERENCE_MATERIAL/Road_Maintenance/060206MaintenanceVSPreservation.doc.

[2] Geiger DR. Pavement preservation definitions: Report. Washington: Federal Highway Administration of the US Department of Transportation; 2005.

[3] The road to sustainable highway spending [Internet]. Washington: Committee for a Responsible Federal Budget; c2015 [cited 2015 Jul 23]. Available from: http://crfb.org/sites/default/files/road_to_sustainable_highway_spending.pdf.

[4] Bureau of Transportation Statistics, US Department of Transportation. National transportation statistics 2015 [Internet]. Washington: US Department of Transportation; c2015 [cited 2015 Jul 23]. Available from: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/NTS_Entire_15Q2_rev.pdf.

[5] Van Dam TJ, Harvey JT, Muench ST, Smith KD, Snyder MB, AlQadi IL. Towards sustainable pavement systems: a reference document. Report. Washington: US Department of Transportation, Federal Highway Administration; 2015. Report No: FHWA-HIF-15-002.

[6] Gransberg DD, Tighe SL, Pittenger D, Miller MC. Sustainable pavement preservation and maintenance practices. In: Gopalakrishnan K, Steyn WJ, Harvey J, editors. Climate change, energy, sustainability and pavements. New York: Springer; 2014. p. 393–418.

[7] Tighe SL, Gransberg DD. Sustainable pavement maintenance practices—research results digest 365. Report. Washington: National Cooperative Highway Research Program; 2011.

[8] LEED® v4 for Neighborhood Development. Report. Washington: US Green Building Council; 2014.

[9] LEED® v4 for building operations and maintenance. Report. Washington: US Green Building Council; 2014.

[10] CH2M HILL, University of Washington, Texas Transportation Institute. INVEST, sustainable highways self-evaluation tool, version 1.2. Report. Washington: US Department of Transportation, Federal Highway Administration; 2015 Sep.

[11] University of Washington, CH2M HILL. Greenroads manual v1.5. Report. Redmond: Greenroads Foundation; 2011 Feb.

[12] Subscribe to Greenroads v2 [Internet]. Redmond: Greenroads Foundation; c2007–2018 [cited 2015 Nov 12]. Available from: https://www.greenroads.org/v2.

[13] Nelson D, Krekeler P. A state-level perspective on the future of sustainability decision making. In: Proceedings of the Transportation Research Board 91st Annual Meeting; 2012 Jan 22–26; Washington, DC, USA; 2012.

[14] Nelson DA, Krekeler P, Rossi M. Incorporating sustainability into NYSDOT's decisions. In: Wagner PJ, Nelson D, editors. Proceedings of the 2011 International Conference on Ecology and Transportation. Raleigh: Center for Transportation and the Environment, North Carolina State University; 2012. p. 861–9.

[15] Illinois Department of Transportation, Illinois Joint Sustainability Group. Illinois–Livable and Sustainable Transportation Rating System and Guide, v2.02. Springfield: Illinois Department of Transportation; 2012 Sep 27.

[16] Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways. Report. Madison: Recycled Materials Resource Center, University of Wisconsin-Madison; 2010.

[17] VicRoads. Integrated VicRoads Environmental Sustainability Tool (INVEST), v1. Report. Melbourne: VicRoads; 2011 Mar.

[18] North American Sustainable Transportation Council, Santa Cruz County Regional Transportation Commission, Portland Bureau of Transportation. STARS fact sheet. Report. Portland: North American Sustainable Transportation Council.

[19] North American Sustainable Transportation Council, Portland Bureau of Transportation. STARS pilot plan application manual, version 1.0. Portland: North American Sustainable Transportation Council; 2012 Jan 10.

[20] North American Sustainable Transportation Council, Portland Bureau of Transportation. STARS pilot project application manual, version 1.2. Portland: North American Sustainable Transportation Council; 2013 Apr 15.

[21] Véron-Okamoto A, Sakamoto K. Toward a sustainability appraisal framework for transport. Report. Manila: Asian Development Bank; 2014 Jan. Report No.: WPS146304.

[22] GreenPave reference guide, version 2.0. Toronto: Materials Engineering and Research Office, Ontario Ministry of Transportation; 2014 Mar.

[23] Jeon CM, Amekudzi A. Addressing sustainability in transportation systems: definitions, indicators, and metrics. J Infrastruct Syst 2005;11:31–50.

[24] Litman T. Developing indicators for comprehensive and sustainable transport planning. Trans Res Record J Trans Res Board 2007;43:10–5.

[25] Jawad D. Sustainable transportation rating tool via traffic impact studies. J Traff Logist Eng 2013;1:30–5.

[26] Triantaphyllou E, Mann SH. Using the analytic hierarchy process for decision making in engineering applications: some challenges. Int J Ind Eng Appl P 1995;2:35–44.

[27] Zietsman J, Ramani T. Sustainability performance measures for state DOTs and other transportation agencies. Report. College Station: Texas Transportation Institute; 2011 Jul.

[28] McCormack SM, Sturgill R, Howell B, Van Dyke C, Kreis D. Green infrastructure. Report. Lexington: Kentucky Transportation Center; 2014 Jun. Report No.: KTC-14-10/SPR447-12-1F.

[29] Southerland M. Evaluation of ecological impacts from highway development. Report. Washington: US Environmental Protection Agency; 1994 Apr. Report No.: EPA 300-B-94-006.