Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

Building Environmentally and Economically Sustainable Transportation Infrastructure: Green Highway Rating System

Jincheol Lee[1]; Tuncer B. Edil, Dist.M.ASCE[2]; Craig H. Benson, F.ASCE[3]; and James M. Tinjum, M.ASCE[4]

Abstract: A rating system is introduced that employs life-cycle analysis techniques to provide a quantitative assessment of the environmental and economic sustainability of highway designs. Energy consumption, greenhouse gas emissions, life-cycle cost, and other factors are considered. On the basis of the score received, a design is assigned a label commensurate with the level of sustainability achieved. Analysis of a pilot project shows that relatively modest changes in a highway pavement design, such as using recycled materials, results in significant environmental and economic benefits. The system can be used to motivate material recycling, resulting in more sustainable construction and growth. **DOI: 10.1061/(ASCE)CO.1943-7862.0000742.** *© 2013 American Society of Civil Engineers.*

CE Database subject headings: Sustainable development; Highways and roads; Recycling; Costs; Life cycles.

Author keywords: Sustainable highway construction; Recycled materials; Life-cycle assessment; Life-cycle cost analysis; BE^{2}ST-in-Highways system; Construction materials and methods.

Introduction

There is considerable evidence that sustainable development can be affected directly or indirectly by engineering design and construction methods (Kibert 2002; Horvath and Hendrickson 1998; U.S. Environmental Protection Agency 2008). The built environment consumes about 40% of all materials extracted annually in the United States (Kibert 2002), and the construction industry is one of the top emitters of greenhouse gases (6% of total industrial-related greenhouse gases in the United States in 2002) (Truitt 2009). These levels of emission and consumption are increasing in response to global economic growth, resulting in a condition that is unsustainable (Kelly 2002; U.S. Energy Information Administration 2010). This long-term unsustainability can be checked in part by altering design objectives and selecting alternative methods and materials for construction (Kibert 2002; Truitt 2009). Because of their size and abundance, buildings and roads are ideal targets for sustainable design and construction initiatives.

Highway construction consumes significant amounts of material and energy and produces a large amount of waste [Gambatese 2005; American Association of State Highway and Transportation Officials (AASHTO) 2008]. For example, constructing a 1-km length of typical two-lane road with flexible pavement consumes 7 TJ of energy (Horvath and Hendrickson 1998). A sustainable approach to highway construction begins with a plan to reuse and incorporate as much of the material already existing on the site as practical (Gambatese 2005). However, lack of quantitative and comparative analysis methods hinders assessment of the economic and environmental benefits that can be achieved using recycled materials in construction.

Historically, the highway construction industry has emphasized three factors: cost, schedule, and quality. These factors do not account explicitly for human demands, environmental impacts, or social responsibility risks (Mendler and Odell 2000). In addition to the conventional factors, sustainable design and construction should explicitly consider the financial, environmental, and social aspects of a project—the so-called triple bottom line (Elkington 1994).

Mendler and Odell (2000) suggest that incorporating environmental and social aspects into design and construction projects requires realignment of the decision strategy from the conventional triangular model balancing cost, schedule, and quality to a pentagon model that also includes social and environmental aspects (Fig. 1). ASCE (2007) suggests that engineers must be responsible for project life cycle and sustainability to transition from designers and builders to leaders. However, lack of analysis methods, examples, and protocols hinders quantification of the benefits associated with sustainable designs and construction methods.

The objective of this study was to develop a transparent and objective method, insofar as possible, for quantitative comparative analysis and rating of sustainable highway construction, referred to as Building Environmentally and Economically Sustainable Transportation Infrastructure-Highways (BE^{2}ST-in-Highways). This approach is consistent with the well-known remark by Lord Kelvin: "When you can measure what you are speaking about, and express it in numbers, you know something about it."

Background

Systems for evaluating sustainability of highway construction are currently being developed in the United States and elsewhere. Six

---

[1] Major, Republic of Korea Marine Corps, P.O. Box #601-206-12, Bongdam, Hwasung, South Korea, 445-899.

[2] Professor Emeritus and Director, Recycled Material Resource Center, Univ. of Wisconsin-Madison, 2228 Engineering Hall, 1415 Engineering Dr., Madison, WI 53706 (corresponding author). E-mail: tbedil@wisc.edu

[3] Wisconsin Distinguished Professor and Director, Office of Sustainability Research and Education, Univ. of Wisconsin, Madison, WI 53706.

[4] Assistant Professor, Dept. of Engineering Professional Development, Univ. of Wisconsin, Madison, WI 53706.

Note. This manuscript was submitted on September 16, 2012; approved on May 21, 2013; published online on May 23, 2013. Discussion period open until January 27, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364/A4013006(10)/$25.00.

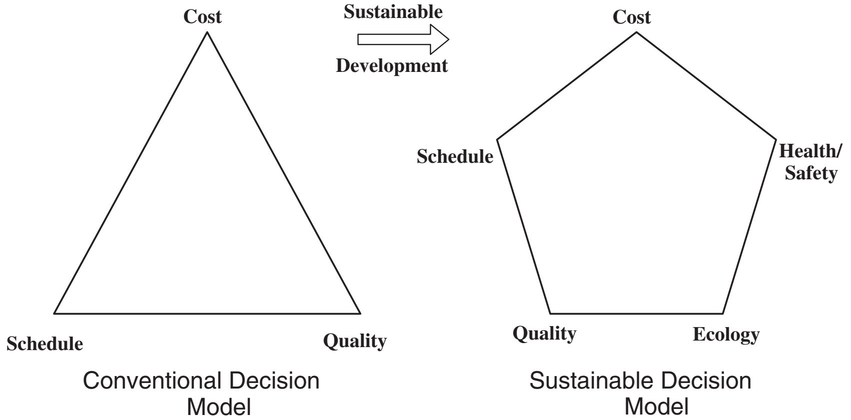


Fig. 1. Conventional and sustainable decision models for construction project (data from Mendler and Odell 2000)

rating systems in the United States (GreenLITES, Greenroads, Envision, STEED, I-LAST, and IN-VEST) are summarized in Table 1. These rating systems, although useful, have the same shortcoming as the Leadership in Energy and Environmental Design (LEED) system for buildings, i.e., those credit-based systems lack objectiveness in the criteria selection and weighting process (Schendler and Udall 2005). The rating procedures in these rating systems (Table 1) are not based on standardized performance metrics; for this reason, the effect of meeting environmental targets in these rating systems cannot be quantified. In some cases, achieving certification or increasing scores becomes the primary goal, regardless of whether the target sustainability objective is achieved. There may be a place and advantage to use the credit-based systems, depending on the objectives of the user. However, if obtaining tangible outputs about how much reduction in environmental impacts can be achieved by adapting better strategies is the objective, the performance-based systems can provide that. In addition, too many criteria are used in some systems (e.g., 40 criteria for IN-VEST) without consideration of their effectiveness or the tradeoffs among criteria.

Carpenter et al. (2007) show how environmental life-cycle analysis approaches can be used to quantify sustainability benefits of using recycled materials in lieu of conventional construction materials in highway construction. Their analyses using an environmental life-cycle assessment tool reveal that significant benefits can be accrued from using recycled materials in the road subbase. However, their analyses did not include rehabilitation events, which are some of the most energy-intensive phases in the highway life-cycle. Carpenter et al. (2007) also did not illustrate how to quantify the economic benefits obtained using recycled materials.

Lee et al. (2010) introduced pairing of comparative environmental and economic life-cycle analyses for assessing the sustainability of highway construction. Their method explicitly includes rehabilitation in the life-cycle assessment using the international roughness index (IRI) as a metric to define when rehabilitation is required. Their analyses with a paired tool reveal that using recycled materials in the base and subbase layers of a highway pavement can result in an increase in environmental and economic benefits while providing longer service life.

Table 1. Rating Systems to Evaluate the Sustainability of Road Construction

Rating system	Attributes
GreenLITES	GreenLITES was developed by New York State DOT to recognize best practices and to measure their performance by evaluating projects incorporating sustainable choices (New York State DOT 2010). There are two certification programs; i.e., a rating program for project designs and a rating program for operations. Highway construction projects are evaluated for sustainable practices on the basis of these programs, and an appropriate certification level (i.e., certified, silver, gold, and evergreen) is assigned on the basis of the total credits received (New York State DOT 2010)
Greenroads	Greenroads is a collection of sustainability best practices that can be applied to roadway construction (Muench 2010). Greenroads consists of required best practices and voluntary best practices. Required best practices should be satisfied as a minimum requirement, whereas voluntary best practices may optionally be considered to enhance sustainability (Muench 2010)
Envision	The Envision is a rating consists of five sections: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Risk. Totally, 60 credits make up this rating system. A 2-page write-up describing each credit includes the intent, levels of achievement, metric, a description of how to achieve a higher level, documentation, and related credits (Institute for Sustainable Infrastructure 2012)
STEED	STEED is a checklist developed by Lochener, Inc., to rate sustainable roadways projects (Demich 2010). STEED consists of 21 elements (e.g., air quality, aesthetic, and livability). Points are awarded if applicants provide a description of the elements they select to obtain points and supporting information on how they address the selected elements (Demich 2010)
I-LAST	I-LAST is a rating system and guide developed by Illinois DOT to evaluate the sustainability of highway projects (Knuth and Fortmann 2010). I-LAST consists of over 150 sustainable items. The scoring process of I-LAST consists of three steps: (1) determining the items applicable to a project; (2) evaluating the total points for the achieved items; and (3) scoring by calculating the percentage of achieved points to the total available points (Knuth and Fortmann 2010)
IN-VEST	IN-VEST is a web-based self-evaluation tool developed by the Federal Highway Administration to measure the sustainability of highway construction (Shepherd 2010). IN-VEST consists of 68 criteria based on sustainability best practices. IN-VEST uses other tools (e.g., GreenLITES and Greenroads) as references. The measurement methods are similar to those of the LEED rating systems (Shepherd 2010)

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

Structure of *BE²ST*-in-Highways

The BE^{2}ST-in-Highways system incorporates standardized measurement methods such as life-cycle assessment (LCA) to quantify environmental impacts and life-cycle cost analysis (LCCA) to quantify economic impacts. The BE^{2}ST-in-Highways system is equipped with a tool to weight sustainability indexes using the analytical hierarchy process (AHP) (Saaty 1980) and is embedded in an Excel spreadsheet for convenient use. Two elements of the Bellagio Principle (Bell and Morse 2008; Piper 2002) were used as guiding principles when developing BE^{2}ST-in-Highways: (1) progress towards sustainable development should be based on measurement of a limited number of indicators using standardized measurement methods, and (2) methods and data employed for assessment of progress should be transparent and accessible. BE^{2}ST-in-Highways can be used to quantify sustainability metrics for highway designs and to assign a label recognizing the sustainability achievement on the basis of these guiding principles.

Criteria embedded in BE^{2}ST-in-Highways were selected by stakeholders (i.e., agency officers, engineers, and scholars) through meetings at the State of Wisconsin Department of Transportation (DOT), and are summarized in Table 2. Each has a specific target. For example:

- The highway construction industry must reduce CO_2 emissions by 20% over the next 50 years (1.3 billion Mg-CO_2e) if global warming potential (GWP) is to remain at the current level [based on Lee et al. (2010)].
- Using fossil fuels to produce energy is directly related to CO_2 emission; thus, the target reduction in energy use is also 20%.
- The target for reduction in life-cycle cost is set at 10% on the basis of recommendations by Egan (1998).
- Using recycled material in highway construction results in substantial reductions in energy and emissions by eliminating or reducing mining and processing of construction materials (Lee et al. 2002). In situ recycling of existing pavement materials also reduces needs for transportation and landfilling. For this reason, in situ recycling is separated from total recycled material content in the criteria used in BE^{2}ST-in-Highways. Targets for the total recycled material content rate and the in situ recycling rate were selected on the basis of the Roadway Standards (Section 460) of Wisconsin DOT (2009); i.e., no more than 20% of recycled asphalt material (if used alone) can be used in a surface layer. Although up to 40% of recycled asphalt material can be used in other layers (i.e., base and subbase layers) based on the standards, the minimum recycling ratio was selected as a target to address every project type, including a pavement resurfacing project. Users of the BE^{2}ST-in-Highways system can set the target volume of the recycled content on the basis of these guidelines. However, targets for these criteria can be adjusted as allowable amounts of recycled material are updated.
- The target for the social cost of carbon (SCC) saving is set at \$24,688/km (\$39,500/mi), which is commensurate with the average annual salary of an individual American (U.S. Census Bureau 2006). The social cost of carbon is the cost to recover damages caused by CO_2 release to the atmosphere and can be used by an agency to account for the social benefits (e.g., spending SCC savings to create new jobs) of reducing GWP into a cost-benefit analysis of sustainable construction efforts [U.S. Department of Energy (U.S. DOE) 2010]. For 2007, the estimates of the average SCC spanned from US\$5 to US\$65 per Mg for different scenarios and at different discount rates (U.S. DOE 2010). The worst-case scenario (US\$65/Mg-CO_2e) was used to evaluate SCC saving in this rating system.
- Other targets, such as water saving and hazardous waste reduction, are practical arbitrary numbers, explained by Lee et al. (2010).

If a target is too easy or difficult to achieve, a rating system has no power of discrimination. Therefore, adjustment of the targets may be necessary.

The BE^{2}ST-in-Highways system consists of two layers, a mandatory screening layer and a judgment layer, as suggested by Dasgupta and Tam (2005). Regulatory and project-specific indicators are initially used in the mandatory screening layer to exclude from further assessment alternative designs that do not satisfy location-specific regulatory and social requirements, including local ordinances and project specific requirements (e.g., preserving a

Table 2. Criteria and Targets in the BE^{2}ST-in-Highways System

Major criteria	Subcriteria	Target	Intent
Mandatory screening	Social requirements including regulation and local ordinances	Satisfied or unsatisfied	Meeting project needs, public perceptions/demands, local official requests/performance requirements/environmental compliance
Judgment	Greenhouse gas emission	20% reduction	1.3 billion Mg of CO_2 in 50 years
	Energy use	20% reduction	Reduce energy use by 20%
	Waste reduction (including ex situ materials)	20% reduction	Reduce resource mining up to 20%
	Waste reduction (recycling in situ materials)	Utilize in situ waste for 20% volume of the structure	Reduce waste to landfill up to 20%
	Water consumption	10% reduction of water consumption	Reduce water consumption up to 10%
	Hazardous waste	20% less hazardous waste	Highway construction in hazard-free manner
	Life cycle cost	10% reduction by recycling	10% annual reduction of life-cycle cost
	Traffic noise	0.5 point for hot mix asphalt Additional 0.5 point for adapting ideas to reduce noise	Prerequisite: traffic noise modeling to maintain moderate living condition
	Social carbon cost saving	Greater than \$24,688/km	Average annual salary for one person by saving social cost of carbon

specific historic site). Projects must meet the screening criteria to complete the evaluation. Alternative designs that satisfy all the requirements at the mandatory screening layer are evaluated further in the judgment layer, as shown in Fig. 2.

Layer 1: Screening

The screening phase is conducted to evaluate mandatory requirements and required prerequisite assessments [e.g., limits on traffic noise and ensuring storm water best management practices (BMPs)]. Regulatory/social indicators and project-specific indicators are used to assess whether the project conforms to a set of laws, regulations, local ordinances, and project-specific requirements. A regulatory/social indicator encompasses criteria required to meet public perceptions or demands and local official requests or requirements.

Submission of an approved environmental impact statement (EIS) is an example of a satisfied regulatory indicator. An EIS is required in the United States to demonstrate conformance with the National Environmental Policy Act (NEPA). A project-specific indicator may address cultural and aesthetic concerns such as preserving a historical site (Dasgupta and Tam 2005). These mandated processes must be satisfied for an assessment to proceed to the judgment indicators.

Screening is conducted on the basis of the official regulatory requirements at the moment screening takes place. Therefore, the most recent regulatory requirements should be incorporated before screening is conducted. For example, even though federal officials may not impose strict requirements, local officials can impose stricter requirements on the use of certain recycled materials. One prerequisite currently is incorporated into the BE^{2}ST-in-Highways system: analysis of storm water management in the contexts of BMPs.

The effectiveness of BMPs for storm water management can be assessed with a cost-benefit analysis with respect to control of storm water volume, total suspended solid (TSS), and their life-cycle costs (Dreelin et al. 2006). The State of Minnesota Department of Transportation (2006) developed a metric to evaluate BMPs with respect to these aspects. The metric provides an analysis tool for both the life-cycle cost and the capacity of storm water volume control. This metric is incorporated into the BE^{2}ST-in-Highways system.

Layer 2: Judgment

Once an alternative design satisfies the requirements in the screening layer, analysis is conducted in the judgment layer. The judgment layer consists of nine metrics (Table 2) to quantify the environmental and economic characteristics of alternative designs in comparison to a reference design: CO_2 emissions in terms of GWP, energy and water consumption, generation of hazardous waste as defined by the U.S. Resource Conservation and Recovery Act (RCRA), life-cycle cost, traffic noise, social cost of carbon, total recycled material content, and in situ recycling rate. A sustainability index between 0 and 1 is assigned to each metric to reflect the degree to which an alternative design meets a sustainability target for each metric (0 = no accomplishment, 1 = target met).

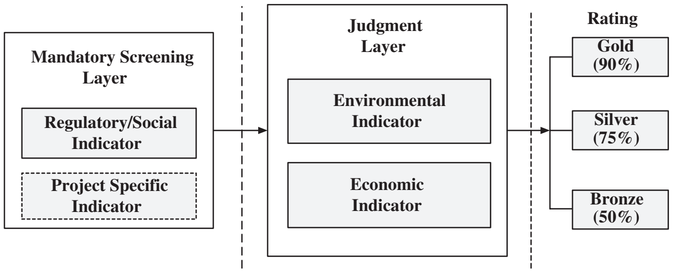


Fig. 2. Structure of the BE^{2}ST-in-Highways system

Two major subsystems are incorporated into the judgment layer for environmental and economic assessment: (1) the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) Version 2.0 (Horvath 2004) for LCA and (2) RealCost [Federal Highway Administration (FHWA 2009)] for LCCA (Fig. 3). Users of the BE^{2}ST-in-Highways system are assumed to be proficient in using PaLATE and RealCost. The accuracy of these subsystems cannot be warranted in the BE^{2}ST-in-Highways system. They are assumed to function properly.

Two individuals conducting a LCA (using PaLATE) and a LCCA (using RealCost) are expected to obtain slightly different results because of the subjectivity inherent in LCA and cost estimating. Therefore, a consistent LCA and cost estimating process is needed to ensure consistency when comparing designs. For example, the input for the PaLATE model (e.g., volume of a material, distance of transportation, and type of construction equipment) should be chosen on the basis of users' best judgment, and the same cost source should be used in the LCCA when comparing reference and alternative designs.

Environmental and economic indicators incorporated into the BE^{2}ST-in-Highways system are imbedded in or interlinked with the Excel spreadsheet software. Input data are entered in and stored in Excel worksheet cells. Thus, the data in the assessment are readily accessible to ensure transparency. Data entered into a data entry field are automatically transferred to corresponding cells in the appropriate underlying worksheet. For example, the "Rating Summary" worksheet contains the data entered in the form shown in Fig. 3.

Life Cycle Assessment

PaLATE was selected for LCA because PaLATE contains environmental and engineering data specifically for evaluating construction and maintenance of pavements using conventional and recycled materials (Horvath 2004). A variety of recycled materials are included in PaLATE (e.g., fly ash, bottom ash, foundry sand) and options are available for means of transportation and types of construction equipment. The user defines the dimensions of each layer in the pavement, the distance between the project site and material sources, and the density of the construction materials. These values yield types and volumes of construction materials, sources and hauling distances, and a set of construction and prescribed maintenance activities. From this information, PaLATE calculates cumulative environmental effects such as energy and water consumption as well as atmospheric emissions (Fig. 3).

Several different sources of information and analysis methods are used in PaLATE to characterize the environmental impact of road construction projects. In PaLATE, the economic input-output life cycle assessment (EIO-LCA) method, a Leontief general equilibrium model of the entire U.S. economy, was employed so that environmental impacts of the entire supply chain would be assessed. As it is shown on the EMF Transport tab of the PaLATE program, the values of environmental impacts are attributed to each economic sector. For example, PaLATE considers consumption of energy and water, emission of greenhouse gases, and production of hazardous waste associated with material transportation and placement as well as mining/processing of conventional materials.

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

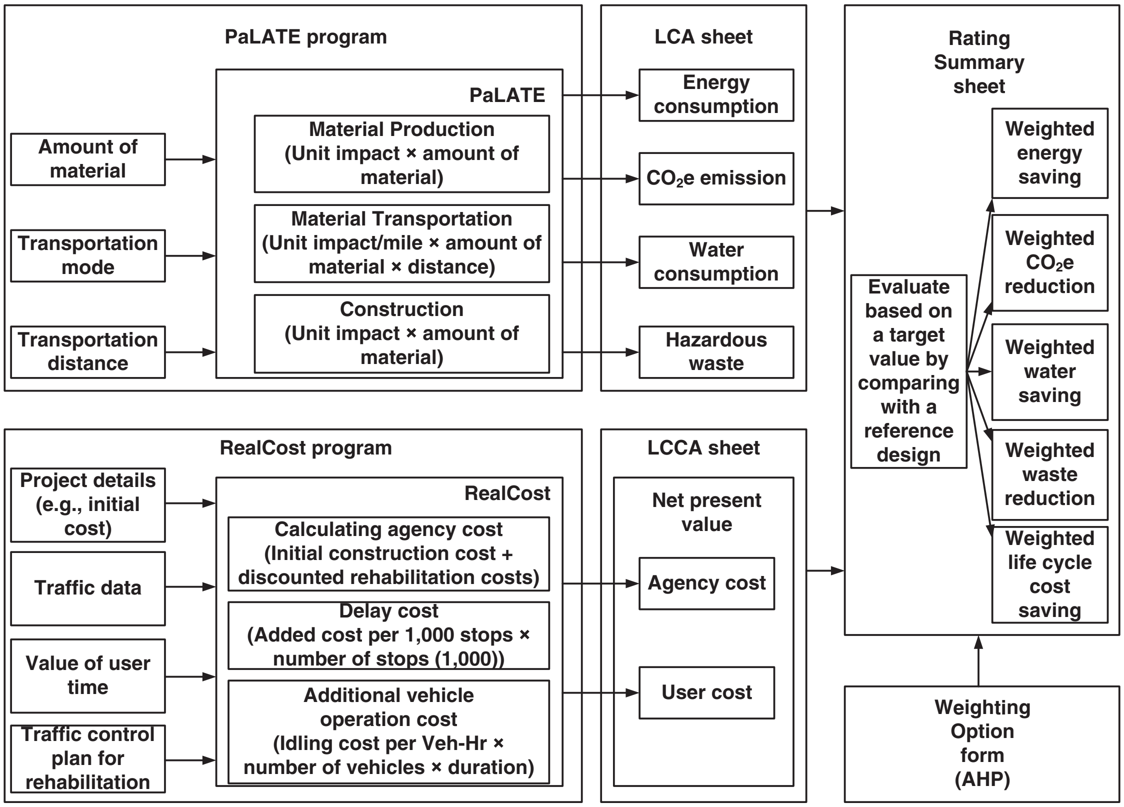


Fig. 3. Process diagram in the BE^{2}ST-in-Highways software (from input to output)

The economy is divided into a square matrix of 480 commodity sectors. The economic model quantifies energy, material, and water use as well as emissions. Because EIO-LCA emission factors are available in metric tons per dollar of sector output, PaLATE uses average U.S. producer prices [\$/t, e.g., from Means (1995)] to calculate emissions per mass of material used. The databases used in PaLATE are described in Horvath (2004).

Life-Cycle Cost Analysis

Using one tool may provide more consistent data outputs than using multiple tools because only one set of assumptions is made. However, PaLATE does not provide many important supporting data that are essential for a life-cycle cost analysis for road construction, such as the data for user costs. PaLATE provides only the material and construction costs, overheads, and profits. So, users may confront more inconsistencies when obtaining life-cycle cost analysis result if they use PaLATE.

For this reason, RealCost version 2.5.2 (FHWA 2009) is used in the BE^{2}ST-in-Highways system to determine the life-cycle cost of a highway, including both agency costs and work zone user costs, for initial construction and rehabilitation events over the lifetime of the highway. Work zone user costs cover both delay and crash costs. Delay costs are costs of time spent in work zones during highway construction or rehabilitations. Crash costs are costs associated with crashes in work zones.

RealCost is an Excel-based spreadsheet program, accompanied by a catalog of individual input parameters, that calculates the net present value of the life cycle of a pavement design using input parameters (e.g., total project cost for each initial construction and rehabilitation, service life, and traffic control plan during initial construction and rehabilitation events) (Fig. 3). The RealCost program provides FHWA's recommendation (i.e., 4 to 5) for the discount rate and the default value is 4. So, the users can choose one of the options. RealCost automates the FHWA best practice LCCA methodology (FHWA 1998).

Social Cost of Carbon

The saving in the social cost of carbon achieved with an alternative design is evaluated in the BE^{2}ST-in-Highways system as the product of the difference in GWP between two designs and the unit SCC (i.e., \$65 in 2007 dollars) (U.S. DOE 2010). A local agency (e.g., Wisconsin DOT) can incorporate this saving into a cost-benefit analysis, especially if a carbon trading or credit scheme exists, such as the program being developed in Australia in 2011 (Parliament of the Commonwealth of Australia 2011). The government probably has to spend money that is commensurate with the social cost of carbon to eliminate or reduce problems caused by carbon emission. However, if carbon emissions can be reduced in the process of road construction, a commensurate financial amount may be directed back into society (e.g., in providing people with jobs which meet the national average annual salary). To make \$24,688 in savings in the social costs of carbon in the process of road construction, about 380 Mg of carbon emission per one kilometer should be reduced, because one Mg of carbon emission costs about \$65 of the social cost of carbon.

Total Recycled Material Content and In Situ Recycling Rate

Two equations are incorporated into the BE^{2}ST-in-Highways system to evaluate in situ recycling efforts and total recycled material content for a highway construction project. The intent is to value strategies that avoid landfilling of old pavement

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

materials as well as the use of recycled materials in lieu of conventional natural resources (e.g., gravel). Total recycled material content (R_T) includes ex situ materials and is computed as

$$R_T = \frac{V_{RA}}{V_{RT}} \tag{1}$$

where V_{RA} = actual volume of recycled construction material used in the project; and V_{RT} = target volume of recycled construction material used in the project. Total recycled material content varies between 0 and 1.

The in situ recycling rate (R_i) is computed by comparing the actual amount of material recycled in situ with the target amount of material recycling in situ:

$$R_i = \frac{V_{Ri}}{V_{RiT}} \tag{2}$$

where V_{Ri} = actual volume of construction material recycled in situ; and V_{RiT} = target volume of in situ recycled construction material used in the project. The in situ recycling rate (R_i) varies between 0 and 1. Recycling old pavement materials in situ reduces transportation requirements and energy consumption during construction. Thus, increasing R_i normally is desirable.

Traffic Noise

Traffic noise modeling is conducted to assess the noise impact of highway traffic in residential areas. Noise is usually defined as any unwanted sound. At very high levels, such as 75 to 80 dBA, noise can cause hearing loss [National Cooperative Highway Research Program (NCHRP) 2002]. The exterior criterion of equivalent noise level (*Leq*) in residential areas is 67 dBA (FHWA 2010). For this reason, maintaining noise below 67 dBA is set as a prerequisite to obtain credits in this criterion. The BE^{2}ST-in-Highways system uses the TNM-LookUp Table (FHWA 2004) to simulate traffic noise. The TNM-LookUp Table reflects the effect of noise levels attributable to changes in traffic volume and construction of noise barriers. Mitigation of noise is addressed by altering the pavement surface, as shown in Table 3. The noise level of rigid pavements is generally 3 dBA higher than that of flexible pavements (Kandhal 2004). Mitigation methods include using rubberized asphalt, stone matrix asphalt, or open-graded friction courses (Table 3).

In addition to traffic noise control, construction noise during a road construction project can cause adverse impacts on the quality of human life. Typically, construction noise is addressed in the project's environmental document and noise analysis report (FHWA 2013). Although it is not adopted in the BE^{2}ST-in-Highways system, evaluation of the impact of construction noise can be considered as a criterion in evaluating the sustainability of road construction. FHWA developed an analysis tool, the FHWA roadway construction noise model (RCNM). The construction noise levels for various stages of a project can be predicted using RCNM.

Table 3. Average Comparative Noise Levels of Different Surface Types (Data from Kandhal 2004)

Pavement surface type	dB(A)	Credit
Open-graded friction courses (OGFC)	−4	1
Stone matrix asphalt (SMA)	−2	
Dense-graded hot mix asphalt (HMA)	0	0.5
Portland cement concrete (PCC)	+3	0

Scoring

A sustainability index (S_i) is assigned to each of the sustainability metrics in the judgment layer. For the metrics evaluated by LCA (energy consumption, water consumption, waste reduction, and CO_2 emission), the sustainability index is computed as

$$S_i = \frac{M_C - M_A}{M_C - M_T} \tag{3}$$

where M_C = sustainability metric for the conventional design; M_A = actual sustainability metric achieved with the alternative design; and M_T = target sustainability metric. The S_i varies between 0 and 1.

Metrics used to measure energy consumption, water consumption, waste reduction, CO_2 emission, life-cycle cost, and social carbon cost result in S_i, whereas the effort to reduce traffic noise is directly assigned points. Because two different conventional surface types (Portland cement concrete (PCC) and hot mixed asphalt (HMA) can be used, the efforts to reduce traffic noise cannot be assessed quantitatively.

In the BE^{2}ST-in-Highways system, alternative designs that save US\$39,500 of SCC [equivalent to creating one new job (U.S. Census Bureau 2006)] are given full credit (1 point).

The total score (S_T) for a design is computed as follows:

$$S_T = 100 \times \frac{1}{9}\sum_{i=1}^{9} \alpha_i S_i \tag{4}$$

where α_i = weights that reflect the relative importance of different metrics; and division by 9 indicates the total possible score when all target values are achieved. These weights must sum to 1.0. In the BE^{2}ST-in-Highways system, the default is equal weights (all metrics of equal importance). However, the BE^{2}ST-in-Highways system provides users with a weighting option using the analytical hierarchy process. In the area of design for the environment (DFE), AHP provides a flexible weight assignment method to various factors in a hierarchical structure by making pairwise comparisons (Eagan and Weinberg 1999).

On the basis of the S_T that is achieved, the project can be awarded a label reflecting the level of accomplishment, e.g., Bronze Green Highway ($S_T = 50$–74%), Silver Green Highway ($S_T = 75$–89%), and Gold Green Highway ($S_T \geq 90\%$). The S_T ranges for the labels can be changed and should be determined by the stakeholders.

AMOEBA: Auditable Outputs of the BE^{2}ST-in-Highways System

AMOEBA graphs (Bell and Morse 2008) are used in the BE^{2}ST-in-Highways system to provide a quantitative and visual assessment of the magnitude of sustainability metrics relative to the targets for each metric. An example is shown in Fig. 4. The perimeter of the graph contains each of the metrics, with the contours corresponding to increasing S_i, with $S_i = 1$ at the perimeter contour. The AMOEBA illustrates metrics where success has been achieved and where more effort is needed to achieve the target. In an ideal setting, the AMOEBA graph would be perfectly symmetric and have all points at $S_i = 1$.

Improving the symmetry of the AMOEBA graph generally corresponds to a more sustainable design (Bell and Morse 2008). For example, the AMOEBA graph on the left of Fig. 4 is highly unbalanced, because accomplishments have been only for a few target metrics. In contrast, the AMOEBA graph on the

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

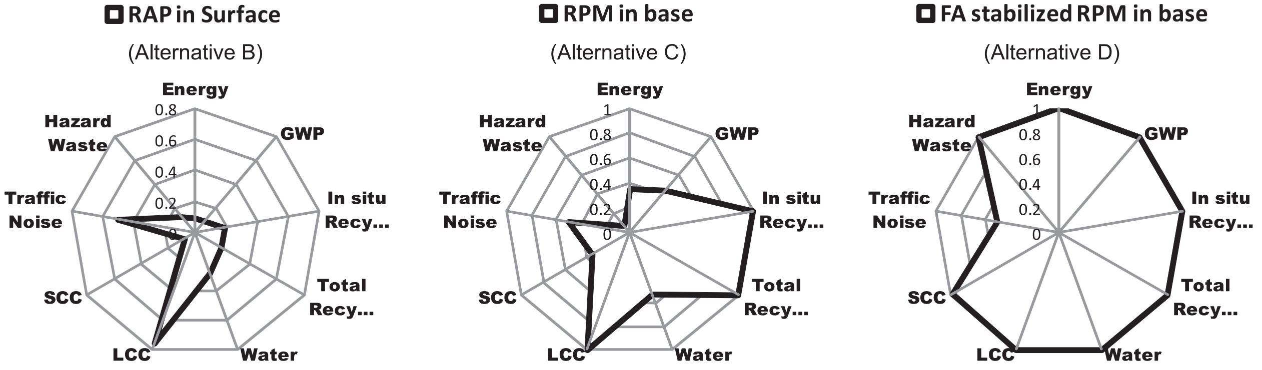


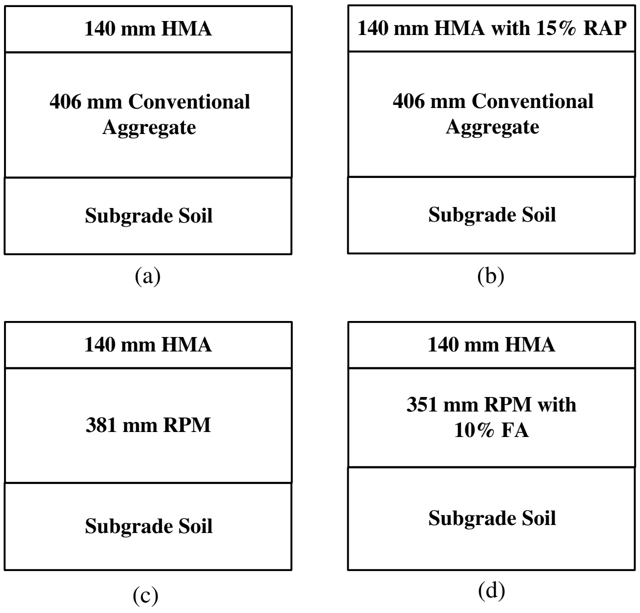
Fig. 4. Auditable outputs of BE^{2}ST-in-Highways system

right of Fig. 4 illustrates good balance, accomplishment in most metrics, and a tendency towards a much higher degree of sustainability.

Practical Application

The flexible pavement portion of the Baraboo Bypass project, a freeway relocation project approximately 1 km west of U.S. 12 near Baraboo, Wisconsin, was assessed using the BE^{2}ST-in-Highways system as an example. To identify the criteria in an objective way in this project, Bell and Morse's theory (2008) was used. Criteria selection was based on whether standardized measurement was available. A stakeholder group participates in developing a vision of sustainable highway construction. Among many candidates of criteria suggested through literature reviews, nine criteria were selected as judgment indicators by a stakeholder group for BE^{2}ST-in-Highways. Some criteria that can be hardly quantifiable were designated as voluntary indicators (e.g., employing roundabouts to improve traffic flow).

Four potential pavement designs, a reference design and three alternatives, were considered. The conventional design (design A) consisted of 140 mm of HMA overlying 406 mm of conventional aggregate base and subgrade (Fig. 5). All of the alternative designs also had 140 mm of HMA but one of them (design B) incorporated 15% recycled asphalt pavement (RAP) into the HMA but maintained the 406 mm of conventional aggregate base. The other two alternative designs (designs C and D) focused on the base course layer: in design C, base course was replaced with a recycled material [recycled pavement material (RPM)], and in design D RPM, was stabilized with 10% cementitious fly ash. The thickness of the base course was 381 and 351 mm, respectively, in designs C and D, reflecting the superior mechanical properties of these alternative base courses. Each alternative design has the same structural capacity as the conventional design. Layer coefficients for RPM and RPM stabilized with fly ash were obtained from Ebrahimi et al. (2012). The RPM has a slightly higher modulus (650 MPa) than a conventional aggregate base (e.g., the Minnesota Department of Transportation Class 5 aggregate that has a modulus of 600 MPa). Recycled pavement material stabilized with fly ash has



(a) (b)

(c) (d)

Fig. 5. Schematic of reference and three alternative pavement designs: (a) reference design; (b) RAP in surface; (c) RPM in BASE; (d) 10% fly ash (FA) stabilized RPM in BASE

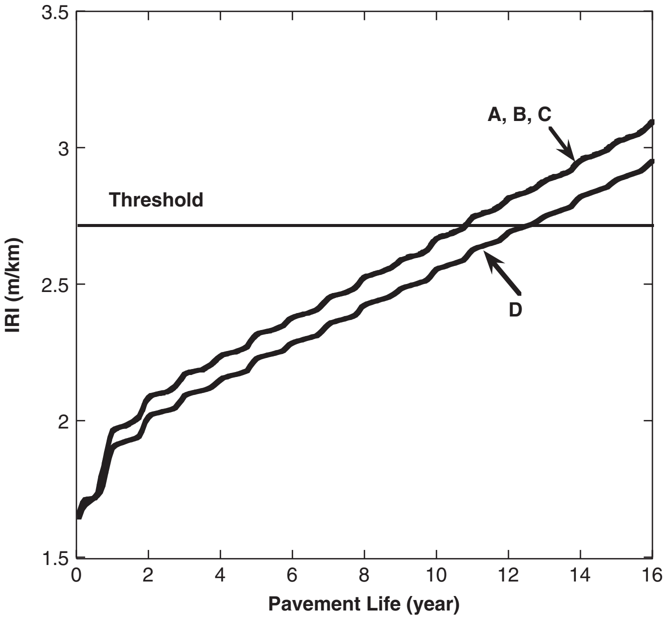


Fig. 6. International roughness index (IRI) of the alternative designs predicted using M-EPDG (Note: the initial IRI are the default values given in M-EPDG)

Table 4. Points Obtained and Total Rating Score

Design	Energy	Global warming potential	Recycled content	Water	Life cycle cost	Social cost of carbon	Traffic noise	Hazard waste	Total score (%)
B	0.1	0.1	0.4	0.3	0.8	0.1	0.5	0.1	26
C	0.4	0.4	2.0	0.5	1.0	0.4	0.5	0.1	58
D	1.0	1.0	2.0	1.0	1.0	1.0	0.5	1.0	94

Note: Design A is the reference design using conventional materials.

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

even higher modulus (845 MPa), which results in a thinner base course. Thus, the alternative design with RPM has a slightly thinner base layer than the reference design that employs crushed aggregate base (Fig. 5).

The service life of each pavement structure was determined using the IRI predicted using the Mechanistic-Empirical Pavement Design Guide (M-EPDG) program (NCHRP 2006). The predicted IRI and the service lives of each of the four pavement designs are shown in Fig. 6. The service life of the pavement was assumed to end when the IRI exceeded 2.7 m/km, which, as indicated by FHWA (1998), requires rehabilitation. For the purpose of this study, the rehabilitation strategy was assumed to be full depth reclamation (FDR) followed with HMA resurfacing. The required number of surface rehabilitations was computed as the quotient of the predicted service life of the pavement design and the anticipated design life of a pavement used by the Wisconsin Department of Transportation (i.e., 50 year). Designs A, B, and C have similar service life (10.8 year), whereas design D has relatively longer service life (12.6 year) because of the high modulus of the base layer (Fig. 6).

BE^{2}ST-in-Highways software was used to assess and rate the alternative designs and to demonstrate the relative impact of material choices. All four alternatives passed the screening phase. For instance, all of the materials (including the recycled materials) are currently permissible for use in Wisconsin. The LCA and LCCA were conducted for the judgment phase, as described in Lee et al. (2010).

Deciding the weighting value of each criterion is a complex decision. The AHP method is employed in the BE^{2}ST-in-Highways system to help decision makers (e.g., road construction planners) find a decision that best suits their goals. The BE^{2}ST-in-Highways system has two options in weighting (equal weighting and weighting using the AHP tool). Although the default weighing values (all metrics of equal importance) were used in this case study because of the limited space of the paper, a more objective weighting can be obtained by using the AHP method embedded in the BE^{2}ST-in-Highways system (see the program details at www.rmrc.wisc.edu).

Air pollutant emissions (e.g., NOx, PM, CO) are not selected as criteria for the Baraboo Bypass project and are not included in hazardous waste. However, those items can be chosen for other projects, and the BE^{2}ST-in-Highway system can show the results because PaLATE provides the data for those emissions.

For the metric energy usage, conventional metric (*Mc*) is 40,729,901 MJ (design A), target metric (*Mt*) is 32,583,921 MJ (20% less than the conventional metric), and actual sustainability metric (*Ma*) is 39,954,076 MJ (design B). Thus $S_i = 0.1$ according to the calculation result using Eq. (3).

The sustainability metrics achieved and the total score are summarized in Table 4 as provided by the BE^{2}ST-in-Highways software for each alternative design in relation to the conventional design (design A).

Alternative D is the most sustainable alternative for the Baraboo Bypass project, with a total score of 94% in accordance with Eq. (4) (i.e., 94% of the total score of 9 is achieved). The score was achieved by a 24% reduction in energy use, a 25% reduction in GWP, and a 29% reduction in life-cycle cost through the reduction of the amount of conventional material uses and the landfilling of useful byproducts. Thus, alternative D would be a Green Highway-Gold. Similarly, Design C is a Green Highway-Bronze, whereas design B failed to achieve a Green Highway certification.

The AMOEBA graphs for these three alternatives are shown in Fig. 4. Alternative B is the least symmetric. Even though using RAP in the surface layer reduces the construction cost significantly (8%), little impact is made on environmental issues (e.g., 2% reduction in energy use and CO_2 emissions). Using RPM in the base course reduces energy use (7%) and water consumption (5%), and has less life-cycle cost (i.e., 24% reduction compared with the reference design). Analyses using the BE^{2}ST-in-Highways showed that using RPM blended with fly ash in the base course as in alternative D is the most sustainable. Using a material with superior properties of RPM stabilized with fly ash result in a thinner design section along with reductions in CO_2 emission, energy use, and cost attributable to substitution of recycled materials.

Summary and Conclusions

The BE^{2}ST-in-Highways sustainability rating system has been described in this paper. BE^{2}ST-in-Highways evaluates projects using a comparative assessment method and rating based on a life-cycle assessment and a life-cycle cost analysis. The evaluation steps include creating alternative pavement designs, predicting the service life of each design (i.e., a reference design and an alternative design), identifying rehabilitation strategies, and conducting LCA and LCCA. The environmental analysis of the conventional and alternative pavements is conducted using the LCA. Four criteria were considered in the assessment: energy consumption, GHG emissions, water consumption, and generation of hazardous wastes, as defined by the U.S. Resource Conservation and Recovery Act. Life-cycle cost analysis is a financially based decision-making tool for long-term assessment of the cost of construction projects that can be used to systematically determine costs attributable to each alternative design over a life cycle period and to make economic comparisons between competing designs (Bull 1993; Kirk and Dell'isola 1998). Rating systems, by their nature, require judgment by the users, such as defining the objectives. These aspects are purposefully subjective in the BE^{2}ST-in-Highways system. However, the BE^{2}ST-in-Highways system employs a quantitative and objective approach in the elements of life-cycle assessment and life-cycle cost analysis, which makes BE^{2}ST-in-Highways unique relative to the other existing rating systems.

The conclusions of this study, on the basis of the example project analyzed, include:

- Using recycled materials in the surface and base course layers yields the highest level of Green Highway Certification (i.e., Green Highway-Gold) and the most benefits in terms of sustainability metrics. In the example case, the following benefits were obtained: 24% energy saving; 25% reduction of global warming potential; and 29% of reduction in life-cycle cost.

- Reductions in energy use and global warming potential are largely attributable to reductions during the material production phase (e.g., mining and processing) achieved by substituting recycled materials for conventional materials. Reductions are also achieved by reducing the thickness of the base layer and the number of rehabilitation events because of longer service life resulting from the superior properties of the recycled materials that were used.
- A reduction in life-cycle cost of 29% was achieved using recycled materials in the example. The largest reduction in life-cycle cost is obtained using recycled material in the base course because of the larger material quantities involved in base course.

The BE^{2}ST-in-Highways rating system is expected to encourage reusing and recycling of materials, resulting in sustainable construction and sustainable growth without the shortcomings found in point systems (e.g., lack of transparency and objectiveness).

Acknowledgments

Support for this study was provided by the Recycled Materials Resource Center. Dr. Pat Eagan of the University of Wisconsin-Madison, Mr. Gary Whited of the Wisconsin Construction and Materials Support Center, and Mr. Steve Krebs of Wisconsin Department of Transportation assisted in the study. The Wisconsin Department of Transportation provided input as a stakeholder. Mr. Charles Coulter of Lafarge North American provided source and cost data for fly ash.

References

American Association of State Highway, and Transportation Officials (AASHTO). (2008). "Primer on transportation and climate change." ⟨http://downloads.transportation.org/ClimateChange.pdf⟩ (Feb. 16, 2009).

ASCE. (2007). "The vision for civil engineering in 2025." *The Summit on the Future of Civil Engineering*, Reston, VA.

Bell, S., and Morse, S. (2008). *Sustainability indicator: Measuring the immeasurable?* Earthscan Publications, London.

Bull, J. W. (1993). "*Life cycle costing for construction*", Chapman & Hall, London.

Carpenter, A. C., Gardner, K. H., Fopiano, J., Benson, C. H., and Edil, T. B. (2007). "Life cycle based risk assessment of recycled materials in roadway construction." *Waste Manage.*, 27(10), 1458–1464.

Dasgupta, S., and Tam, E. K. L. (2005). "Indicators and framework for assessing sustainable infrastructure." *Can. J. Civ. Eng.*, 32(1), 30–44.

Demich, G. (2010). "STEED-A transportation green scale for continuous improvement." *Proc., 1st T&DI Green Streets & Highway Conf*, ASCE, Reston, VA.

Dreelin, E. A., Fowler, L., and Carroll, C. R. (2006). *Managing stormwater in your community: A guide for building an effective post-construction program*, Center for Watershed Protection, Ellicott City, MD.

Eagan, P., and Weinberg, L. (1999). "Application of analytic hierarchy process techniques to streamlined life-cycle analysis of two anodizing processes." *Environ. Sci. Technol.*, 33(9), 1495–1500.

Ebrahimi, A., Kootstra, B.Edil, T. B., and Benson, C. H. (2012). "Practical approach for designing flexible pavements using recycled roadway materials as base course." *Road Mater. Pavements Des.*, 13(4), 731–748.

Egan, S. J. (1998). *Rethinking construction*, Dept. of Trade and Industry, Westminster, UK.

Elkington, J. (1994). "Towards the sustainability corporation: Win-win-win business strategies for sustainability development." *Calif. Manage. Rev.*, 36(2), 90–100.

Federal Highway Administration (FHWA). (1998). *Life-cycle cost analysis in pavement design—In search of better investment decision*, Washington, DC.

Federal Highway Administration (FHWA). (2009). "RealCost version 2.5.2." ⟨http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm⟩.

Federal Highway Administration (FHWA). (2004). "TNM version 2.5 look-up tables." ⟨http://www.fhwa.dot.gov/environment/noise/tnm/tn_ver25lu.htm⟩ (Mar. 7, 2009).

Federal Highway Administration (FHWA). (2010). "Highway traffic noise." ⟨http://www.fhwa.dot.gov/environment/htnoise.htm⟩ (Sep. 7, 2010).

Federal Highway Administration (FHWA). (2013). "Construction Noise." ⟨http://www.fhwa.dot.gov/environment/noise/construction_noise/⟩ (May 20, 2013).

Gambatese, J. A. (2005). "Sustainable roadway construction: Energy consumption and material waste generation of roadways." *Proc., Construction Research Congress 183*, ASCE, Reston, VA, 1–13.

Horvath, A. (2004). *Pavement life-cycle assessment tool for environmental and economic effects (PaLATE) user manual*, Recycled Materials Resource Center, Durham, NH.

Horvath, A., and Hendrickson, C. (1998). "Comparison of environmental implication of asphalt and steel-reinforced concrete pavements." *Transportation Research Record 1626*, Transportation Research Board, Washington, DC, 105–113.

Institute for Sustainable Infrastructure. (2012). "Envision checklist." ⟨http://www.sustainableinfrastructure.org/portal/envision2/checklist.cfm⟩.

Kandhal, P. S. (2004). "Asphalt pavements mitigate tire/pavement noise." *Hot Mix Asphalt Technol.*, 9(2), 22–31.

Kelly, T. D. (2002). "Raw materials and technology fuel U.S. economic growth." *Min. Eng.*, 54, 17–21.

Kibert, C. J. (2002). "Policy instruments for a sustainable built environment." *J. Land Use Environ. Law*, 17(2), 379–394.

Kirk, S. J., and Dell'isola, A. J. (1998). "*Life cycle costing for design professionals*", McGraw-Hill, New York.

Knuth, D., and Fortmann, J. (2010). "The development of I-LAST Illinois —Livable and sustainable transportation." *Proc., 1st T&DI Green Streets and Highway Conf*, ASCE, Reston, VA.

Lee, J. C., Edil, T. B., Tinjum, J. M., and Benson, C. H. (2010). "Quantitative assessment of environmental and economic benefits of using recycled construction materials in highway construction." *Transportation Research Record 2158*, Transportation Research Board, Washington, DC, 138–142.

R.S. Means (1995). "R.S. Means building construction cost data." R.S. Means, Kingston, MA.

Mendler, F. S., and Odell, W. (2000). *The HOK guidebook to sustainable design*, Wiley, New York.

Minnesota Department of Transportation. (2006). "Impact of alternative stormwater management approaches on highway infrastructure: Guide for section of best management practices." *MN/RC-2005-49A*, Vol. 1, St. Paul, MN.

Muench, S. (2010). "About greenroads rating system." Univ. of Washington ⟨http://www.greenroads.us/347/about-the-greenroads-rating-system.html⟩ (Nov. 19, 2010).

National Cooperative Highway Research Program (NCHRP). (2002). "Guidebook for assessing the social and economic effects of transportation projects." *NCHRP Rep. 456*, National Academy Press, Washington, DC.

National Cooperative Highway Research Program (NCHRP). (2006). "Mechanistic-empirical design of new and rehabilitated pavement structures." ⟨http://www.trb.org/mepdg/software.html⟩ (Feb. 16, 2009).

New York State Department of Transportation. (2010). "NYSDOT sustainability & GreenLITES." ⟨https://www.nysdot.gov/programs/greenlites/repository/GreenLITES-sustainability-flyer-handout.pdf⟩ (Nov. 19, 2010).

Parliament of the Commonwealth of Australia. (2011). *Clean energy bill 2011(exposure draft)*, Canberra, Australia.

Piper, J. M. (2002). "CAE and sustainable development evidence from UK case studies." *Environ. Impact Assess. Rev.*, 22(1), 17–36.

Saaty, T. L. (1980). *The analytical hierarchy process*, McGraw-Hill, New York.

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.

Schendler, A., and Udall, R. (2005). “LEED is broken, let’s fix it.” ⟨http://www.igreenbuild.com/cd_1706.aspx⟩ (Jul. 28, 2010).

Shepherd, G. (2010). “FHWA’s sustainable highways self-evaluation tool.” ⟨http://www.transportation.org/sites/aashto/docs/FHWA%20Sustainable%20Highways%20Tool%20-%20AASHTO%2010-29-10%20v2%20(2)final.pdf⟩ (Nov. 19, 2010).

Truitt, P. (2009). *Potential for reducing greenhouse gas emission in the construction sector*, U.S. Environmental Protection Agency, Washington, DC.

U.S. Census Bureau. (2006). “Annual demographic survey.” ⟨http://pubdb3.census.gov/macro/032006/perinc/new03_028.htm⟩ (Nov. 19, 2009).

U.S. Department of Energy (U.S. DOE). (2010). “Energy conservation program: Energy conservation standards for small electric motors final rule.” ⟨http://www.federalregister.gov/articles/2010/03/09/2010-4358/energy-conservation-program-energy-conservation-standards-for-small-electric-motors⟩ (Sep. 9, 2010).

U.S. Energy Information Administration. (2010). “International energy outlook 2010—Highlights.” ⟨http://www.eia.doe.gov/oiaf/ieo/highlights.html⟩ (Sep. 9, 2010).

U.S. Environmental Protection Agency. (2008). “Study on increasing the usage of recovered mineral components in cement and concrete projects.” *Publication EPA-530-R-08-007*, Washington, DC.

Wisconsin Department of Transportation. (2009). “2010 standard specifications.” ⟨http://roadwaystandards.dot.wi.gov/standards/stndspec/index.htm⟩ (Feb. 15, 2010).

Downloaded from ascelibrary.org by University of Wisconsin - Madison on 11/15/13. Copyright ASCE. For personal use only; all rights reserved.