# EVALUATION OF VARIABLES AFFECTING SUSTAINABLE HIGHWAY DESIGN USING THE BE$^2$ST-IN-HIGHWAYS$^{TM}$ SYSTEM

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## ABSTRACT

Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways (BE$^2$ST-in-Highways$^{TM}$) was developed to provide a quantitative methodology for rating the benefits of sustainable highway construction. The methodology is grounded in quantitative metrics so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This rating system can be utilized by the highway industry to help incoporate sustainable elements into projects more easily at the forefront but also in any phase of the project. To illustrate the proposed rating system, a pilot project (Baraboo Bypass) was evaluated using eight alternative designs. The pilot project evaluation indicates that use of smaller quantities of raw material in highway construction results in a project that consumes less energy and emits less $CO_2$, thus resulting in higher sustainability scores. The superior material properties of some recycled materials (e.g., high resilient modulus of fly-ash-stabilized recycled pavement material) reduce material consumption and also extend the service life of the highway structure, a decisive factor affecting the sustainability rating. The results of this study illustrate design strategies that offer a greater sustainability in the BE$^2$ST-in-Highways$^{TM}$ system.

## INTRODUCTION

Sustainable development is defined as the ability to “meet the needs of the present without compromising the ability of future generations to meet their own needs” (*1*). To measure the sustainable development, Elkington (*2*) suggested three equally important components (i.e., environmental, financial, and social aspects). Kibert (*3*) claimed that construction industry should employ efforts to green the built environment (e.g., reduce resource consumption, reuse resources to the maximum extent possible, recycle built environment end-of-life resources and use recyclable resources). In accordance with this movement, there is a growing social demand to make highway construction more sustainable without compromising conventional construction goals (i.e., cost, quality, and schedule) because highway construction projects consume large amount of energy and natural materials, produce wastes, and generate greenhouse gases (*4,5*). In response, efforts have been made to quantitatively evaluate the sustainability of highway construction projects. For example, Carpenter et al. (*6*) showed how a life cycle assessment (LCA) method can be applied to quantify the environmental impacts of using recycled materials in roadway construction. Lee et al. (*7*) introduced the pairing of comparative environmental and economic life cycle analyses for assessing highway construction. This coupled method explicitly includes rehabilitation activities in the life cycle assessment using the international roughness index (IRI) as a metric to define when rehabilitation is required.

Based on the approaches suggested by Capenter et al. (*6*) and Lee et al. (*7*), a quantitative assessment system, Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways (BE$^2$ST-in-Highways$^{TM}$), was developed to measure and rate the sustainability of highway construction (*8*). The BE$^2$ST-in-Highways$^{TM}$ system employs quantitative assessment techniques to assess overall life cycle performance associated with a highway construction project. Energy, greenhouse gas emissions, and service life are evaluated in a quantitative framework that can be used to compare alternative highway construction strategies from a holistic perspective and in the context of system-wide targets established in a weighted approach by stakeholders. The methodology is grounded in quantitative metrics rather than an arbitrary point system so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This transparency reduces the potential for ‘gaming’ of the rating system, which is a common problem associated with sustainability rating systems in the building construction industry (*9*).

The BE$^2$ST-in-Highways$^{TM}$ system is applied to a pilot project (the Baraboo Bypass in southcentral Wisconsin) using eight alternative designs to assess the design strategies in terms of reduced raw material quantities and use of recycled materials to consume less energy and emit less CO$_2$. The superior material properties of some recycled materials (e.g., high resilient modulus of fly-ash-stabilized base layer) are shown to contribute to reducing material consumption and extending the service life of the highway, a decisive factor affecting the sustainability performance in terms of the sustainability score achieved. The findings in this study are expected to help project designers choose strategies to adopt sustainable initiatives in highway construction.

## DESCRIPTION OF THE PILOT PROJECT AND THE BE$^2$ST-IN-HIGHWAYS$^{TM}$ SYSTEM

Since environmental and economic benefits accrued by recycling the existing old pavement can be evaluated using the BE$^2$ST-in-Highways$^{TM}$ system, a relocated freeway (Baraboo Bypass) approximately1km west of existing US-12 near Baraboo, Wisconsin, was selected as a pilot project, The first portion of this improvement, from I-90/94 south to the existing four-lane roadway at Tarrytown Road (9.2 km), is scheduled for 2009 - 2011(*10*). Constructing 21,703 m$^2$ of concrete pavement and 34,681 Mg of hotmix asphalt is included in the 3.7 million dollar project. For the purpose of this research, eight potential pavement designs were considered in the analysis of constructing a 1.6-km-long section of Baraboo Bypass (Table 1). The thickness of the surface layer, whether flexible or rigid pavement, was kept constant at a minimal value. The base layer thickness was changed in each design to generate the same pavement structural number using the appropriate layer coefficients for each alternative material as provided by (*11*).

**TABLE 1 Schematic of Eight Alternative Pavement Designs**

| Design # | Surface type | Recycled material in surface | Thickness of surface (mm) | Base type | Thickness of base (mm) | Recycled Material in base |
|---|---|---|---|---|---|---|
| F-1 Reference | HMA | No | 140 | Aggregate | 152 | No |
| F-2 | | RAP (15%) | 140 | Aggregate | 152 | No |
| F-3 | | No | 140 | RPM with 10% FA | 94 | RPM with 10% FA |

| | | | | | | |
|---|---|---|---|---|---|---|
| F-4 | | RAP (15%) | 140 | RPM with 10% FA | 94 | RPM with 10% FA |
| R-1 | PCC | FA 15% | 254 | Aggregate | 152 | No |
| R-2 | | FA 30% | 254 | Aggregate | 152 | No |
| R-3 | | FA 15% | 254 | RPM with 10% FA | 94 | RPM with 10% FA |
| R-4 | | FA 30% | 254 | RPM with 10% FA | 94 | RPM with 10% FA |

*RAP: Reclaimed Asphalt Pavement, RPM: Recycled Pavement Material, FA: Fly-Ash, HMA: Hot Mix Asphalt, PCC: Portland Cement Concrete.

The BE$^2$ST-in-Highways$^{TM}$ system is a comparative quantitative assessment and rating system that can be used during the planning and designing of highway construction projects to incorporate sustainability goals in highway construction. Two layers of indicators (i.e., mandatory screening and judgment indicators) suggested by Dasgupta and Tam (*12*) are used in the system (Figure 1). The regulatory and project specific indicators are used initially to exclude from further assessment some of the alternatives which do not satisfy given requirements of the criteria (*12*). Criteria required for meeting project needs, public perceptions or demands, local official requests or requirements can be included in regulatory indicators. A project specific indicator can address cultural and aesthetic concerns, e.g., preserving a specific historical site (*12*).

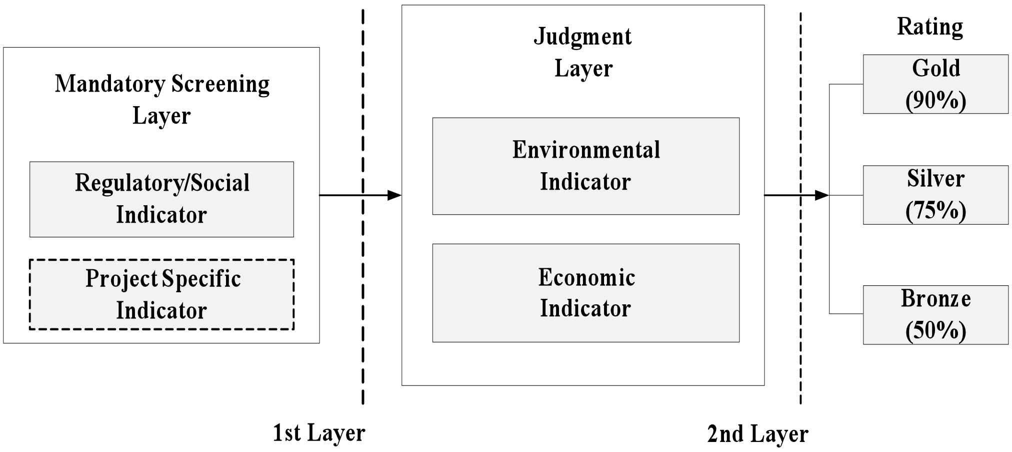


**FIGURE 1 Schematic structure of the BE$^2$ST-in-Highways$^{TM}$ system.**

Table 2 depicts a summary of the developed criteria, target values, and objectives in the assessment system. Table 2 also defines the scope of the system: the rating system is restricted to issues related to quantifiable construction materials and processes. The boundary of the system can be expanded in the future as new technologies (e.g., new performance indicators, information technologies, etc.) become available. With the criteria and their target values established, weights are assigned to each criterion along with credit levels. An equally weighted system consisting of 2 points for each criterion, resulting in 18 total points, is the default in the BE$^2$ST-in-Highways$^{TM}$ system and is used here for demonstrative purposes.

**TABLE 2 Criteria and Target Values in the Assessment System**

| Major Criteria | Subcriteria | Target (1 point each) | Intention |
|---|---|---|---|
| Mandatory Screening | Social Requirements Including Regulation & Local Ordinances | Satisfied or unsatisfied | Meeting project needs, public perceptions/demands, local official requests/performance requirements/environmental compliance |
| Judgment | Greenhouse Gas Emission | 10% reduction | 0.85 billion tons of $CO_2$ in 50 yrs |
| | | 20% reduction | 1.7 billion tons of $CO_2$ in 50 yrs |
| | Energy Use | 10% reduction | Reduction of energy use by 20% |
| | | 20% reduction | |
| | Waste Reduction (Including *Ex situ* Materials) | 10% reduction | Reduction of resource mining up to 20% |
| | | 20% reduction | |
| | Waste Reduction (Recycling *In situ* Materials) | Utilize *in situ* waste for 10% volume of the structure | Reduction of waste to landfill up to 20% |
| | | 20% | |
| | Water Consumption | 5% reduction of water consumption | Reduction of water consumption up to 10% |
| | | 10% reduction | |
| | Social Carbon | Greater than | Average annual salary for 1 person |

| | | | |
|---|---|---|---|
| | Cost Saving | $12,344/km | by saving social carbon cost |
| | | Greater than $24,688/km | |
| | Life Cycle Cost | 5% reduction by recycling | 10% annual reduction of life cycle cost |
| | | 10% reduction by recycling | |
| | Traffic Noise | 1 point for HMA | Prerequisite: traffic noise modeling to maintain moderate living condition |
| | | Additional 1 point for adapting ideas to reduce noise | |
| | Hazardous Waste | 10% less hazardous waste | Highway construction in hazard-free manner |
| | | 20% less hazardous waste | |

In an actual application, stakeholders would select the weights and credits. Weights based on the importance ascribed to each criterion can be assigned using the analytical hierarchy process (AHP) (*13*). A tool for computing the weighting value with AHP is provided as a separate software package. Judgment on the sustainability of a highway project is expressed in terms of the quantitative difference between a reference design and proposed alternative design(s). Since the score of an alternative design is calculated relative to the reference design, care should be taken to fully define the reference highway construction design in as realistic manner as possible. A conventional design approach in which sustainability concepts are explicitly not incorporated can be used as a reference design.

## RATING PROCEDURE

Since the longevity of a highway structure determines the required amount of energy and materials, the initial step must estimate the project's theoretical service life. Rehabilitation strategies can be based on this estimated service life. Once these construction and rehabilitation plans are determined, a screening phase is conducted to evaluate mandatory requirements (e.g., checking the conformance with laws, ordinances, regulations, specifications, and standards) and required prerequisite assessments (i.e., traffic noise and stormwater best management practices). After all requirements and prerequisites are satisfied, judgment assessments (e.g., life cycle assessment using PaLATE (*14*), life cycle cost analysis using RealCost (*15*), calculation of recycled material content, and analysis of Social Carbon Cost (SCC) (*16*)) are conducted.

## APPLICATION OF THE RATING SYSTEM

### Rating Procedure

The BE$^2$ST-in-Highways$^{TM}$ software was used for assessing and rating alternative designs for the pavement structure of an actual highway project to demonstrate the functionality of the system. The layer coefficient is the relative ability of an unit thickness of a material to sustain design traffic load (*17*). The structural number is an index of capacity of the pavement structure to sustain the design traffic load. Since the structural number is obtained for each layer by multiplying the layer coefficient and the thickness of the layer, the recommended thickness of a layer to achieve a certain structural number can be derived if the layer coefficient is known. The structural number assigned to the base course in the Baraboo Bypass was 1.2. The sum of the structural numbers of each layer is the structural number of the pavement structure.

Eight alternative designs for the Baraboo Bypass project were evaluated with the BE$^2$ST in-Highway$^{TM}$ system following the same procedure used for the Burlington Bypass project in (*8*). The procedure starts from the screening phase. The alternatives are considered to conform to all requirements (i.e., laws, project specifications, etc.). The screening phase is followed by estimating the service life of the competing designs using the Mechanistic Empirical Pavement Design Guide (M-EPDG) program (*18*). The surface layer thickness of the typical hot mix asphalt (HMA) surface type section is 140 mm. Given the design conditions (see Table 3), the thickness of the Portland cement concrete (PCC) layer commensurate with the thickness of the HMA layer was determined to be 254 mm. The AASHTO method (*17*) was used for the calculation of the thickness of the PCC layer.

**TABLE 3 Input Variables for Calculation of Thickness of Rigid Pavement**

| Input variable | Value |
|---|---|

| | |
|---|---|
| Total design ESALs ($W_{18}$) | 10,592,300 |
| Reliability level in percent | 90 |
| Combined standard error ($S_0$) | 0.4 |
| Initial serviceability index ($P_i$) | 4.5 |
| Terminal serviceability index ($P_t$) | 3 |
| Elastic modulus (Ec) in kPa | 30,799,543 |
| Modulus of rupture (S'c) in kPa | 4,826 |
| Drainage factor | 1 |
| Modulus of subgrade reaction in kN/m$^3$ | 123,365 |

The thickness of the base layer was calculated using layer coefficients of 0.08 and 0.13 recommended in (*11*) for aggregate and RPM stabilized with 10% fly-ash, respectively. Analyses were conducted to predict the service life of each design using the M-EPDG program with moduli of 123 and 197 MPa for aggregate and RPM stabilized with 10% fly-ash, respectively, recommended in (*11*). The predicted service lives of each of the eight pavement designs are shown in Figure 2 and summarized in Table 4 in terms of the IRI. The flexible pavement sections degrade steadily (increasing IRI), whereas the rigid pavement sections show little degradation followed by rapid cracking (Figure 2).

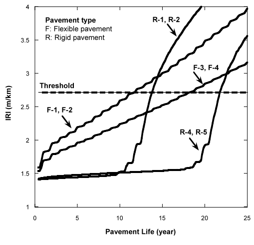


**FIGURE 2 International roughness index of the eight alternative designs predicted using M-EPDG.**

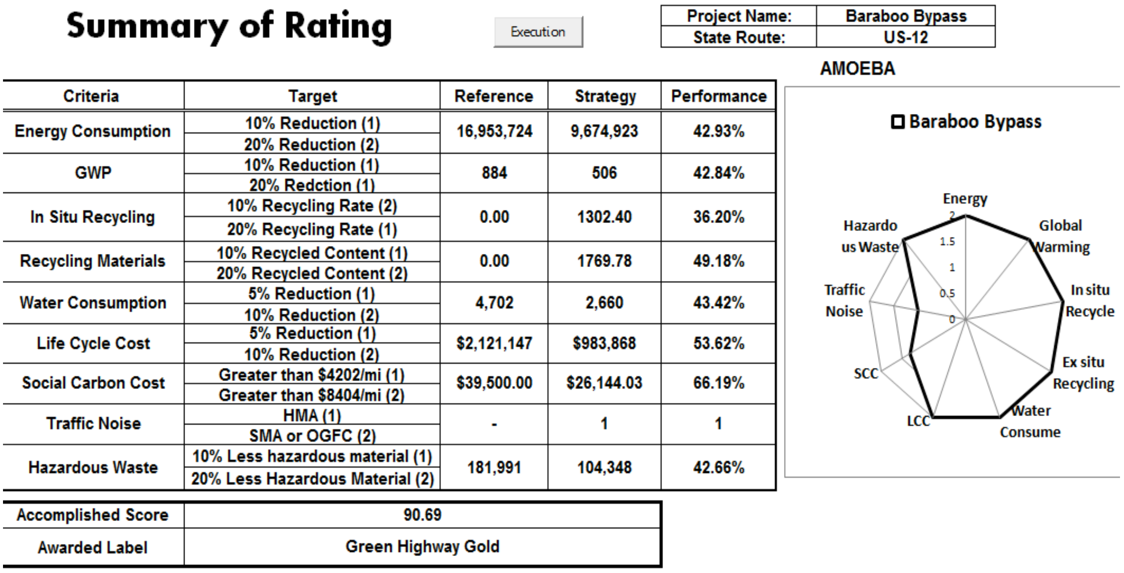
Once the service life of each alternative is obtained, pavement rehabilitation strategies can be evaluated. For the purpose of this investigation, all rehabilitation strategies were assumed to include HMA resurfacing. An IRI of 2.7 m/km indicates that a selected pavement has reached its terminal serviceability, and at least one rehabilitation activity is required (*19*). The required number of surface rehabilitations was computed by dividing the period of analysis by the expected service life of a structure (see Table 4). Four designs (F-3, F-4, R-3 and R-4) have relatively longer service lives (approximately 20 years). The feature that these four designs have in common is that the base layer is stabilized with fly-ash to increase its stiffness.

**TABLE 4 Predicted Service Life and Number of Rehabilitations Required During Analysis Period**

| Design | Service life | Number of rehabilitations required for 50 years |
|---|---|---|
| F-1, F-2 | 11.8 | 4 |
| F-3, F-4 | 18.3 | 2 |
| R-1, R-2 | 13.8 | 3 |
| R-3, R-4 | 21.8 | 2 |

## Assessment Results

Life cycle assessment, life cycle cost analysis, calculations of recycled material contents and *in situ* recycling rates, and evaluations of traffic noise were conducted as described in (*7*,*8*), and their results were compared with the reference design. Design F-1 was selected as the reference design because this conventional design method uses conventional construction materials and has the maximum adverse environmental and economic impacts compared to the other designs. Ratings were conducted based on calculations of performance values and comparison with the assigned target values using the BE$^2$ST-in-Highways program (Figure 3).



Summary of Rating

| Project Name: | Baraboo Bypass |
|---|---|
| State Route: | US-12 |

| Criteria | Target | Reference | Strategy | Performance |
|---|---|---|---|---|
| Energy Consumption | 10% Reduction (1)<br>20% Reduction (2) | 16,953,724 | 9,674,923 | 42.93% |
| GWP | 10% Reduction (1)<br>20% Redction (1) | 884 | 506 | 42.84% |
| In Situ Recycling | 10% Recycling Rate (2)<br>20% Recycling Rate (1) | 0.00 | 1302.40 | 36.20% |
| Recycling Materials | 10% Recycled Content (1)<br>20% Recycled Content (2) | 0.00 | 1769.78 | 49.18% |
| Water Consumption | 5% Reduction (1)<br>10% Reduction (2) | 4,702 | 2,660 | 43.42% |
| Life Cycle Cost | 5% Reduction (1)<br>10% Reduction (2) | $2,121,147 | $983,868 | 53.62% |
| Social Carbon Cost | Greater than $4202/mi (1)<br>Greater than $8404/mi (2) | $39,500.00 | $26,144.03 | 66.19% |
| Traffic Noise | HMA (1)<br>SMA or OGFC (2) | - | 1 | 1 |
| Hazardous Waste | 10% Less hazardous material (1)<br>20% Less Hazardous Material (2) | 181,991 | 104,348 | 42.66% |

| Accomplished Score | 90.69 |
|---|---|
| Awarded Label | Green Highway Gold |

**FIGURE 3 Final screen shot of the BE$^2$ST-in-Highways$^{TM}$ program for case F-4.**

### *Environmental Impacts and Energy Consumption*

Global warming potential for each design is shown in Figure 4 in terms of $CO_2$ equivalents ($CO_2$e). Most of the $CO_2$e (90%) is produced during material production by heavy equipment operation. Since mining and crushing processes require heavy equipment, use of recycled materials that require minimal or no processing can significantly reduce $CO_2$e emissions. Design F-3 and F-4 reduced $CO_2$e levels by more than 40% by reducing the thickness of the base layer, and therefore reducing material consumption.

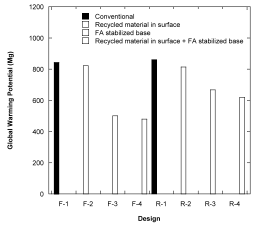


**FIGURE 4 Global warming potential of the eight alternative designs.**

Four of the pavement designs (F-3, F-4, R-3 and R-4) consume relatively less energy during their entire life cycle as shown in Figure 5. These four designs use less material (i.e., thinner layers and fewer rehabilitation events due to longer service lives), and therefore less energy is required for material extraction, transportation, and construction.

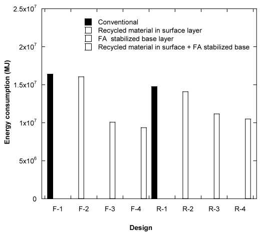


**FIGURE 5 Energy consumption for the eight alternative designs.**

Water consumption, shown in Figure 6, shows that four of the pavement designs (F-3, F-4, R-3 and R-4) consume relatively less water during their entire life cycle. Changing the base layer designs has greater potential to reduce water consumption (see design F-3 and F-4). These four designs use less material (i.e., thinner layers and fewer rehabilitation events due to longer service lives), and therefore less water is required for material extraction, transportation, and construction. Overall, the greatest environmental benefit and energy savings accrued through the reduction of material use or replacement of conventional construction materials with recycled materials. More than 90% of the reduction in environmental problems (e.g., $CO_2$ emission and hazardous waste production) and energy consumption in a highway life cycle are obtained through the material production phase by avoiding mining processing and oil refining for asphalt binder.

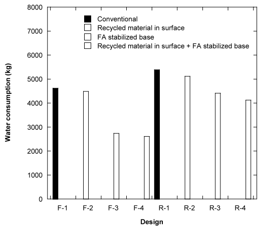


**FIGURE 6 Water consumption for the eight alternative designs.**

*Life Cycle Cost*

A comparison of life cycle costs for each of the design strategies is shown in Figure 7. Among the design alternatives evaluated, F-1, F-2, R-1and R-2 have higher life cycle costs. Their more frequent rehabilitation requires more material consumption. The reference design, F-1 ranks highest in life cycle cost among the eight alternatives because conventional materials are used. The designs incorporating recycled material have superior material properties relative to conventional materials, and therefore the life-cycle costs are lower. Therefore, highway construction with recycled material content of high quality can result in significant financial savings along with the benefits of sustainability. While the use of recycled material in this case study reduced costs for both flexible and rigid structures, the relative impacts compared to the reference case depend on pavement type.

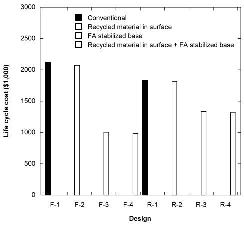


**FIGURE 7 Life cycle cost of the eight alternative designs.**

## Rating Results

The environmental and economic attributes of the seven alternative designs were normalized to the reference design (F-1). Fuzzy logic (*20*) was used for normalization. The main aim of the normalization was to calculate performance based on the relative magnitude of the performance metric (*20*,*21*). The total score is the sum of the points obtained as a fraction of 18 total points.

Normalization results are tabulated and presented in Table 5. Design F-4 obtained the highest score. Design F-4 achieved the highest scores in almost every criterion. Compared to the reference design (F-1), Design F-4 has 43% lower energy consumption and 43% lower global warming potential. The life cycle cost was reduced by 54% by replacing 49% of the construction material with recycled material, which has superior material properties (e.g., higher resilient modulus) extending the service life and also lower initial cost. It is not necessarily true that in every instance use of recycled materials will result in higher ratings even though in general it will improve the ratings. Additionally $16,967 of SCC per km of highway was saved. The SCC is "an estimate of the monetized damages associated with an incremental increase in carbon emission in a given year" (*16*). The purpose of the SCC calculation is to allow a state agency (e.g., Wisconsin DOT) to incorporate the social benefits of reducing global warming potential into the cost-benefit analyses of sustainable construction efforts (*16*).

**TABLE 5 Points Obtained and Total Rating Score**

| Design | Energy | GWP* | Recycle | Water | LCC* | Traffic Noise | Hazard Material | SCC* | Total Score |
|---|---|---|---|---|---|---|---|---|---|
| F-2 | 0.2 | 0.2 | 2.2 | 0.3 | 0.2 | 1.0 | 0.3 | 0.8 | 29 |
| F-3 | 2.0 | 2.0 | 4.0 | 2.0 | 2.0 | 1.0 | 2.0 | 1.3 | 91 |
| F-4 | 2.0 | 2.0 | 4.0 | 2.0 | 2.0 | 1.0 | 2.0 | 1.4 | 91 |
| R-1 | 1.0 | 0.0 | 0.4 | 0.0 | 2.0 | 0.0 | 2.0 | 0 | 30 |
| R-2 | 1.4 | 0.4 | 0.7 | 0.0 | 2.0 | 0.0 | 2 | 0.1 | 37 |
| R-3 | 2.0 | 2.0 | 4.0 | 1.0 | 2.0 | 0.0 | 2.0 | 0.7 | 49 |
| R-4 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 0.0 | 2.0 | 0.9 | 72 |

*GWP: Global Warming Potential, LCC: Life Cycle Cost, SCC: Social Cabon Cost

## CONCLUSION

The potential benefits of employing green strategies (e.g., using recycled materials instead of conventional materials) in a highway construction project have been evaluated and described using the BE$^2$ST-in-Highways$^{TM}$ system. Currently the system boundary of BE$^2$ST-in-Highways$^{TM}$ is restricted only to pavement design. Extention of sustainability approach to the entire span of project activities (e.g., in other elements of the right of way such as barriers and guide rails) would further enhance the environmental and economic benefits. However, as illustrated subsequently, the results of this pilot project evaluation indicate that modest changes only to a pavement design can yield significant environmental and economic benefits: 43% reduction in energy; 43% reduction in GWP; and 54% reduction in life cycle cost. The superior material properties of some recycled materials (e.g., high resilient modulus of fly-ash-stabilized recycled pavement material) reduce the amount of material consumption and also extend the service life of the highway structure, and therefore less adverse environmental and economic impacts are produced.

As illustrated in the Baraboo Bypass pilot project, the BE$^2$ST-in-Highways$^{TM}$ system employs life cycle analysis techniques to provide an overall assessment of the environmental and economical impacts associated with a highway construction project. Energy consumption, greenhouse gas emissions, service life, and life cycle cost are evaluated in a quantitative framework that can be used to compare alternative construction strategies from a holistic perspective. The methodology is grounded in quantitative metrics rather than an arbitrary point system so that a transparent linkage exists between the project rating and the sustainable practices employed in design and construction. This transparency reduces the potential for 'gaming' of the rating system.

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