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Original Article/Research

Sustainability assessment of roadway projects under uncertainty using Green Proforma: An index-based approach

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Abstract

Growing environmental and socioeconomic concerns due to rapid urbanization, population growth and climate change impacts have motivated decision-makers to incorporate sustainable best practices for transportation infrastructure development and management. A "sustainable" transportation infrastructure implies that all the sustainability objectives (i.e., mobility, safety, resource efficiency, economy, ecological protection, environmental quality) are adequately met during the infrastructure life cycle. State-of-the-art sustainability rating tools contain the best practices for the sustainability assessment of infrastructure projects. Generally, the existing rating tools are not well equipped to handle uncertainties associated with data limitations and expert opinion and cannot effectively adapt to site specific constraints for reliable sustainability assessment. This paper presents the development of a customizable tool, called "Green Proforma" for the sustainability assessment of roadway projects under uncertainties. For evaluating how well the project meets sustainability objectives, a hierarchical framework is used to develop the sustainability objective indices by aggregating the selected indicators with the help of fuzzy synthetic evaluation technique. These indices are further aggregated to attain an overall sustainability index for a roadway project. To facilitate the decision makers, a "Roadway Project Sustainometer" has been developed to illustrate how well the roadway project is meeting its sustainability objectives. By linking the sustainability objectives to measurable indicators, the "Green Proforma" paves the way for a practical approach in sustainable planning and management of roadway projects.

Keywords: Sustainability assessment; Roadway infrastructure; Uncertainty analysis; Decision-making; Fuzzy synthetic evaluation technique

1. Introduction

As a consequence of urbanization, there is an increasing demand for services from the currently aging, insufficient and vulnerable roadway infrastructure (Adeli, 2002). As per United Nations report "World Urbanization Prospects", the world urban population will increase by 70% between 2011 and 2050 (United Nations Department of Economic and Social Affairs, Population Division, 2014). Such an alarming situation will increase the stress on the

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existing infrastructure and certainly demands its large scale expansions in urban areas. Building, expanding and operating additional roadway infrastructure consumes a significant amount of natural resources, produces large volumes of waste and requires extensive human capital (Morrissey et al., 2012). Therefore, "smart" or "sustainable" planning, design and construction approaches are needed in developing the roadway infrastructure (Shen and Zhou, 2014; Curwell et al., 1999; Walton et al., 2005). Since the report published by Brundtland Commission (1987), sustainable development has become a matter of prime importance for all development activities and the need to measure and track the sustainability of roadway infrastructures has emerged (Marsden et al., 2010; Anderson, 2012; Martland, 2011; Mills and Attoh-Okine, 2014).

Transportation projects involve planning, design, construction, operation and end-of-life phases and each phase requires interaction among certain stakeholders for the implementation of best practices. Traditionally, a successful delivery of transportation projects requires the completion of required project scope with high quality and within reasonable budget and schedule. "Sustainability" is not the same as cost, time and quality dimensions of project, rather, it is the infrastructure life cycle performance that shows how well it *contributes* to the society and environment i.e., whether it is causing more damage or improving the existing societal and environmental values/conditions (Lee et al., 2013; Muench et al., 2011). Given the highlighted challenges of limited resources, population growth and rapidly deteriorating infrastructure, the necessity to "manage sustainability by measuring it" is rapidly recognized by the construction, management and engineering professionals in the civil engineering industry.

Several rating systems have been developed to measure and track the sustainability of built environment, e.g. LEED-ND® (USGBC, 2009), Greenroads™ (Muench et al., 2011), Envision™ (Institute for Sustainable Infrastructure, 2012), etc. The state-of-the-art rating systems provide guidelines to incorporate the best practices in different phases of the project lifecycle and to evaluate the sustainability of infrastructure projects (Simpson et al., 2014). Most of these rating systems are based on the sustainability indicators (to evaluate the sustainability achievements) and benchmarks (as indicator target or reference values). However, researchers and decision-makers have highlighted several desirable features that are deficient in these rating systems (Andreas et al., 2010). In a recent study by Simpson et al. (2014), self-assessment feature, customizability of criteria, and the choice of relevant criteria were identified as some of the desirable features generally lagging in transportation infrastructure rating systems. Curz et al. (2012) identified the need for a flexible and holistic transportation rating tool that could be customized to fit the assessment requirement of any transportation project. Certainly, the existing systems have not been developed to handle uncertainties in indicator values and benchmarks due to data limitations and expert opinions (Shiau et al., 2015; Alsulami and Mohamed, 2014; Yoe et al., 2010; Gasparatos et al., 2009; Hunt et al., 2008; Boschmann and Kwan, 2008). Furthermore, aggregating all the indicators into a single score can eclipse the underlying performance across project sustainability objectives (Haider et al., 2016a).

Benchmarks are the target or reference values for sustainability indicators, and the benchmarking process allows the decision makers to establish the desired level of performance for sustainable initiatives or practices. Some recently developed benchmarking methodologies offer continuous benchmark functions instead of discrete numbers (Haider et al., 2016b); however, the rating systems lack this capability (López and Sánchez, 2011). Existing rating systems like I-LAST (Illinois – Livable and Sustainable Transportation) (IDOT and IJSG, 2012) and Greenroad™ have fixed set of points and level of benchmarks for each of the sustainability practice e.g. 20% of recycled material used qualifies for 2 points (Sharifi and Murayama, 2013; Gasparatos et al., 2009; Hacking and Guthrie, 2008; Munda, 2006). This limits the experts' ability to modify the importance of sustainable practices and the benchmarks depending on the geographic, climatic and technological limitations (Chow et al., 2013; Bueno et al., 2015). The results of some of these rating systems like GreenLITES (Leadership in Transportation and Environmental Sustainability) (NYSDOT, 2012) in the form of overall scores and/or arbitrary certification levels (e.g. gold, platinum, and silver) may be misleading in some cases. For instance, limited number of applicable best practices from rating systems may result in lower scores but it does not necessarily imply that the project did not adequately meet all the sustainability targets, i.e., same yardstick cannot be used to assess the sustainability of all the projects. Thus, rigid point scoring system in the state-of-the-art rating tools, without addressing the uncertainties, misrepresents the sustainability results and often leads to point-hunting at the cost of possibly significant environmental and socioeconomic impacts (Sharifi and Murayama, 2013; Oliveira and Pinho, 2010; Singh et al., 2009; Cole, 2005; Walton et al., 2005; Becker, 2004). Global Sustainability Assessment System (GSAS) (GORD, 2015) is one of the few tools that awards '−1' score to the criteria that potentially leads to negative impacts if not met during project implementation. Awarding negative scores is useful as it emphasizes best practices which can be implemented in specific circumstances.

Moreover, establishing the benchmarks or targets for sustainability indicators in early project planning phase is inherently uncertain due to the vagueness in available information and expert opinion when assigning numeric values to linguistic scales such as 'low' or 'high'. For example, establishing target values for 'recycled material used' in the early project phases requires knowledge of the availability of recycled materials, its applicability for constructing roadway components, the type of existing pavement structure, geometrics of the roadway, and topography of the area. These initially established (default) benchmarks can provide some useful information about the sustainability targets for the project, but these values must be adapted to project-specific constraints for reliable sustainability assessment. Hence, the sustainability assessment methods should be able to handle expert opinion and imprecise information while establishing benchmarks and inputs for the indicators (Gil and Duarte, 2013; Yoe et al., 2010; Hunt et al., 2008; Foxon et al., 2002).

The main objective of this research is to develop a framework to assess the sustainability of roadway projects under uncertainty using the indicators from Greenroads™ rating system (Muench et al., 2011). The proposed framework, finally presented as an Excel-based tool, efficiently deals with the uncertainties identified above and illustrates the results in the form of performance indices across the sustainability objectives and an overall index for the roadway project. The developed tool is not intended to replace the existing rating systems, rather, the tool enables the customizability and flexibility of the existing rating systems.

The remainder of the paper is organized as follows: Section 2 presents the methodology adopted to carry out this research. Furthermore, a sustainability assessment process is proposed that supports adaptive management technique to improve the sustainability criteria of roadway projects. In Section 3, scenario analysis has been conducted to demonstrate the influence of decision maker's preferences on the sustainability outputs obtained from the Green Proforma.

2. Methodology

2.1. Sustainability assessment framework

Fig. 1 illustrates steps involved in generating indices showing the extent of sustainability achievements in a roadway project. A sustainability evaluation hierarchy is developed to link the indicators of best practices with the desired objectives of a roadway project. The indicators are obtained from Greenroads™ Rating System (Muench et al., 2011). Fuzzy synthetic evaluation technique is used to handle uncertainties in information related to data variables required for calculating the indicators, aggregated indices (correspond to sustainability objectives) as well as for the overall index. An Excel-based tool called the "Green Proforma for Roadway Projects" was developed based on the framework and FSE technique. Finally, scenario analysis was conducted to demonstrate the influence of decision maker's preferences on the sustainability outputs obtained from the Green Proforma.

2.2. Development of sustainability criteria

The criteria for sustainability assessment depends significantly on the project stakeholders' understanding of sustainable development e.g. investors may refer to an economically viable project as the most sustainable one (Boschmann and Kwan, 2008; Clevenger et al., 2013). State-of-the-art rating systems often characterize sustainability with triple bottom lines (TBL) i.e., economic, environmental and social dimensions (Reza, 2013). However, Anderson (2012) and Jeon et al. (2010) suggested that the TBL concept is difficult to apply practically to a roadway project due to the complexity in characterizing TBL dimensions with specific objectives and criteria. Anderson (2008) described sustainability in civil engineering as a quality of the system that adequately sustains both "human values" and "natural laws". This description is more practical for engineers as it specifically brings systems such as roadways into the perspective (Anderson, 2012). Therefore, this study applies this definition to develop a hierarchy (shown in Fig. 2) that characterizes roadway system's sustainability

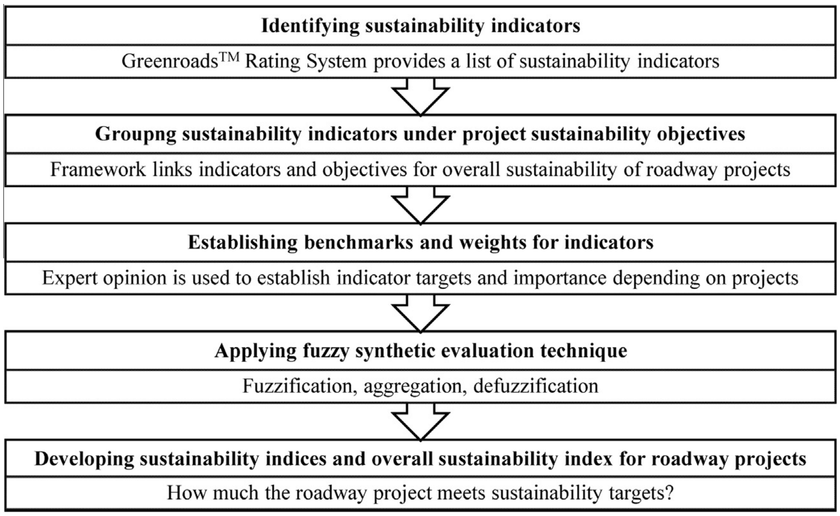


Figure 1. Proposed framework for sustainability assessment of roadway projects.

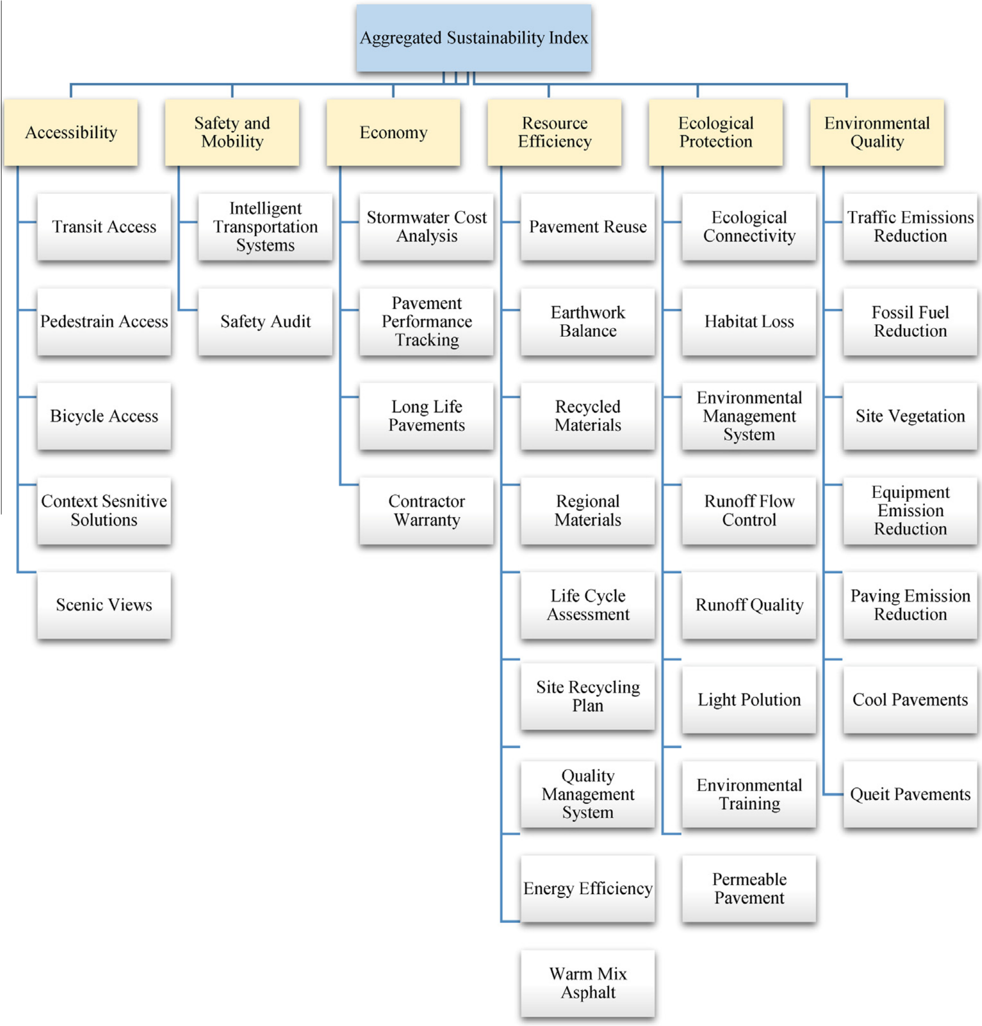


Figure 2. Hierarchical structure linking sustainability indicators and objectives.

with specific objectives and criteria that support “natural laws” and “human values”. Each criterion is evaluated using specific sustainability indicators that are available from state-of-the-art guidelines known as Greenroads™ (Muench et al., 2011).

2.2.1. *Sustainability objectives for human values*

Sustainability objectives and indicators related to “Human Values” include.

2.2.1.1. Accessibility. The roadway infrastructure should provide pedestrian, transit, vehicle and bike users, an adequate access through the use of best practices and proper consultation with stakeholders. Securing public opinion and incorporating it in planning the transportation access can significantly contribute to the success of roadway project by ensuring that roadway infrastructure fits its context and meets the expectations of the community. Also, it is important to consider the variety of travel modes supported by the planned roadway infrastructure. Active transportation is regarded as an important sustainability component in planning the transportation systems. Some of the key indicators enhancing active transportation may include improving bicycle and pedestrian access to public services by developing new and improving existing bike storage facilities, sidewalks, shared bike and pedestrian lanes and planning transit-oriented developments. These indicators are shown to increase the modal share for less carbon intensive modes of travel.

2.2.1.2. Safety and mobility. The roadway infrastructure development should ensure safe and smooth travel of people using sidewalks, bicycles, and vehicles. This objective may require implementation of surveillance systems to gather information on existing traffic conditions, enforcing traffic control through various applications and providing traveler information. An important indicator in this objective is the use of intelligent transportation systems (ITS) to provide lane control, variable speed limits, dynamic message signs and traveler information for efficient flow of traffic. During the operation phase, a periodic safety audit can also ensure the effectiveness of existing road safety scheme by identifying the problematic areas and recommending measures for improvements. These features can significantly reduce road accidents and delay times.

2.2.1.3. Economy. The roadway infrastructure should be planned, designed, constructed and maintained to achieve economic efficiency. This objective requires the stakeholders to take a lifecycle perspective on minimizing the cost of roadway infrastructure by considering operation and maintenance (O&M) costs with construction expenses. In addition, user costs should also be considered as with any O&M activity, there can be traffic delays that can cost the users in terms fuel usage and lost productivity. Some significant indicators in this objective can include the periodic evaluation of pavement condition, risk-based planning for rehabilitation and renewal of pavements, documenting the life cycle cost analysis for storm water management according to standard methods, providing warranties of pavement life in contract documents, etc. These features can help in ensuring long-term availability of budgets for the roadway infrastructure and minimize user costs.

2.2.2. Sustainability objectives for natural laws

Sustainability objectives and indicators related to "Natural Laws" include.

2.2.2.1. Resource efficiency. The roadway infrastructure development should minimize the use of virgin or natural resources. This objective requires the use of construction materials that have minimum environmental impacts from raw material extraction to construction to the end-of-life phases. Existing pavement structure can be reused based on their condition to optimize the use of base and sub-base materials. Land development should follow the best engineering principle of balancing cut and fill whenever achievable. Recycled material obtained from the demolition of existing structures should be appropriately used. Use of energy efficient construction equipment and having an appropriate quality management system are important features to achieve resource efficiency in roadway projects.

2.2.2.2. Environmental quality. The roadway development activities should minimize the deterioration in air and acoustic quality of the local environment by implementing measures such as congestion pricing, vegetation planning, and noise abatement measures. Appropriate selection of pavement material followed by application of adequate measures to reduce pollution and noise impacts in the surrounding environment during construction and maintenance can certainly enhance the environmental quality of the project. Other important indicators included for this objective are the use of cool pavements, paving equipment emission reduction and the use of quiet pavements. This objective can be achieved by conducting a comprehensive environmental assessment study for both the construction and operation phases of the project.

2.2.2.3. Ecological protection. The roadway infrastructure development should protect existing water bodies, land, and ecological systems. The existing environmental setting of the project area can be maintained and even improved during construction and operation phases with the appropriate structural and hydrologic design of turf reinforcing grids, porous asphalt pavements, and permeable pavers. The design of new roadway should strive to maintain and enhance the existing pathways of terrestrial and aquatic animals by providing ecological connectivity. Loss of habitat should be minimized with the careful geometric design of roadway projects. Runoff pollution should be reduced by designing appropriate storm water retention and detention structures at appropriate locations. Another indicator in this objective can include the hiring of a contractor that has a formal environmental management system in place. By implementing these features, the project not only strives in reducing the damage to existing natural environment but also protects and enhances existing natural features.

The decision-makers are often more interested in aggregated measures to save the time and resources required to consider the indicators individually (Poveda and Young, 2015; Singh et al., 2009). Sahely et al. (2005) reasoned that indicators alone are not sufficient for determining the state of progress toward sustainability, and the aggregated indices are more useful as they signify the relative state of achievements for specific sustainable development goals or objectives. Aggregated measures operationalize the sustainability initiatives and also assist in identifying the needs for upgradation of infrastructure systems. Fig. 2 illustrates the hierarchical framework that synthesizes the information obtained from different indicators to develop aggregated indices (representing the objectives) identified earlier for roadway infrastructure projects.

2.3. Weights and benchmarks of criteria

Relative weights represent how important a given indicator is to the sustainability objectives of the roadway project. A direct assignment procedure based on Hwang and Yoon (2012) can be applied to evaluate the relative weights of indicators as it is simple and requires less user effort as compared to other techniques such as Analytic Hierarchical Process (AHP). The direct assignment process can be applied using a linear and discrete 1–5 point scale represented by corresponding linguistic descriptions: "Not Applicable", "Very Low"; "Low"; "Medium"; "High"; and "Very High". The numbers corresponding to the given linguistic scale of importance can be generated and then normalized across the complete list of indicators underneath each category of sustainability objectives to generate relative weights on a 0–1 scale.

The benchmarks of sustainability indicators represent the desired level of performance for a project on linguistic scales. A common classification of performance levels can be developed to characterize benchmarks for all qualitative and quantitative indicators. In this study, a five-level linguistic has been used to develop benchmarks for all the indicators (see Table 1). The benchmarks for indicators depend on the technological capability, site features, climatic factors and regulatory requirements related to the project. The definition of weights and benchmarks are critical for reliable sustainability assessment of roadway projects. The universal discourse for all the indicators is provided in Table A1 (Appendix A) that categorizes indicators and benchmarks according to the sustainability objectives.

2.3.1. *Quantitative indicators*

Some indicators can be quantified as specific numeric variables; for example, the % of pavement surface designed as quiet pavement. The top row values in Table 1 represent the *least* values and bottom row values represent the *highest* values for each linguistic scale. Due to vagueness in expert opinion, these ranges can also overlap which means that the boundaries of numeric benchmarks are unclear between the linguistic scales of performance. Fuzzy logic has been applied to this type of problem in different studies, and its application is discussed in more detail in the following sections.

2.3.2. *Qualitative indicators*

Qualitative indicators represent the subjective criteria; for instance, "Context Sensitive Solutions" includes some form of descriptive features that can vary across the linguistic performance levels identified earlier (refer to Table 1). Detailed assessment of this indicator may need considerations to different aspects, such as need of project, public involvement process and results, transportation modes considered, long-term planning, etc. The "partial consideration" performance level may require minimum information whereas full consideration may require generating all the pertinent documents depending on how comprehensively the experts define these benchmarks.

2.4. *Fuzzy synthetic evaluation*

Fuzzy logic is one of the most effective techniques to handle uncertainties due to linguistic information, approximate reasoning and imprecise information (Reza, 2013; Waheed et al., 2011; Rajani et al., 2006; Sadiq and Rodriguez, 2004). In reality, human understanding or expert opinion is best represented with degrees of certainty (fuzzy logic) rather than absolute certitude (classical logic) (Ross, 2009). In this study, fuzzy synthetic evaluation (FSE) technique has been used that makes the use of fuzzy theory to develop fuzzy membership functions for each indicator listed in Fig. 2. The fuzzy membership functions quantitatively model uncertainties in indicator benchmarks and inputs based on the confidence level of experts. FSE technique involves following basic steps to evaluate overall system performance (Sadiq et al., 2004a,b):

Step 1: Fuzzification: Fuzzifying the indicator benchmarks and generating indicator fuzzy sets.
Step 2: Aggregation: Aggregating the indicator fuzzy sets.
Step 3: Defuzzification: Defuzzifying the aggregated fuzzy sets to crisp performance scores.

2.4.1. *Fuzzification*

The inputs and benchmarks for indicators have been fuzzified by Khatri et al. (2011), Rajani et al. (2006), and Sadiq and Rodriguez (2004) in their studies to generate the indicator fuzzy sets. The benchmarks given in Table 2 are converted to triangular fuzzy functions for each linguistic scale as shown in Fig. 3. The average value for a linguistic scale is assigned a membership value of 1.0 while the extreme values are assigned 0.0 membership. After the development of roadway infrastructure, the sustainability indicators can be measured by obtaining the raw data from on-site records. The on-site data can also be uncertain e.g. reduction in earthwork achieved by balancing cut and fill volumes. In such cases, an uncertainty handling mechanism that allows the user to provide a range of the sustainability indicator values is useful. Khatri et al. (2011) applied an approach based on the fuzzy set theory to map the uncertain inputs over the pre-defined benchmark's membership functions. In this study, a similar approach has been used with some modifications. An input value of 30–40% is also plotted as a TFN in a similar manner. The intersection of fuzzy input function with the benchmark membership functions is shown in Fig. 3. For multiple intersections with a benchmark function, a maximum value is chosen and the numbers are further normalized across the linguistic scale to generate a fuzzy set as shown in Table 3. For qualitative indicators, a similar procedure was adopted using pseudo-numeric values to fuzzify and plot membership functions.

2.4.2. *Prioritization and aggregation*

Aggregation process synthesizes information (e.g. fuzzy sets) in one unit from the bottom of the hierarchy to generate the information for elements present at higher hierarchical levels in the same units. In this study, the fuzzy sets of sustainability objectives are obtained by aggregating the fuzzy sets of underlying sustainability indicators. Aggregation is simply the sum-product of indicator weights and fuzzy sets. The fuzzy sets of sustainability objectives are further aggregated to determine an overall sustainability fuzzy set for a complete roadway system.

2.4.3. *Defuzzification*

The aggregated fuzzy sets are converted to crisp numbers using defuzzification methods to simplify the representation of system sustainability. In this study, the "*center of gravity*" method has been chosen to defuzzify the aggregated fuzzy sets for sustainability objectives and overall sustainability index. In the "*center of gravity*" method, the center of gravity of the fuzzy set is located, and

Table 1
"Quiet pavements" & "Context Sensitive Solutions" adapted from Muench et al. (2011).

Indicator	Unit or Measure	V. Poor	Poor	Fair	Good	V. Good
Quiet pavement	% of the total regularly trafficked pavement surface area designed to reduce tire pavement noise levels at or below certain standards	0 40	20 70	40 80	70 90	80 100
Context Sensitive Solutions	Consideration to Context Sensitive Solutions in the project design	No consideration	–	Partial consideration	–	Full consideration

Table 2
Example of input for the benchmark of indicators.

Indicator	Measure	V. Poor	Poor	Fair	Good	V. Good
Long-life pavements	% of regularly trafficked lanes designed for long-life (>=40 years)	0 40	20 60	40 70	60 80	70 100

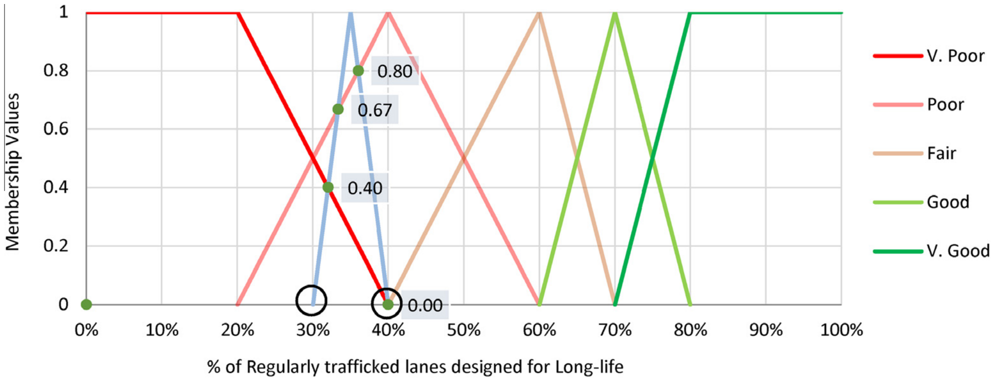


Figure 3. Benchmark and input membership functions for "% of regularly trafficked lanes designed for long life".

corresponding x-scale value is returned as a crisp number. Subsequently, the defuzzified values of sustainability objectives are plotted on a radar diagram. Fig. 4 shows the results of a hypothetical simulation. The thermometer shows the overall defuzzified sustainability index, and the diagram summarizes the roadway system sustainability in a single display called the "Roadway Project Sustainometer." The sustainability indices are mapped on color-coded zones representing performance levels similar to those identified earlier for each indicator benchmarks. The linguistically defined overall sustainability index guides the planners and decision-makers regarding the level of sustainability achieved by the project. The zones do not have defined boundaries as the benchmarking process recognizes the fuzziness or vagueness in establishing the specific and non-overlapping extreme performance values for each indicator on a linguistic scale.

2.5. Application of Green Proforma

Green Proforma evaluates the sustainability for the planning, design, construction and operation phases of roadway infrastructure projects (see Fig. 5). The stakeholders can customize indicators' benchmarks and weights using the Green Proforma depending on project-specific constraints. The proposed sustainability assessment process is based on Deming's Wheel or Plan-Do-Study-Act (PDSA) cycle. The PDSA cycle is applied to improve continuously the product or process quality, however, in this case, sustainability of roadway project is improved (Taylor et al., 2014). The tool can be applied in the following three phases.

Table 3
Fuzzy set representing the belongingness of indicator values to the linguistic scales for the indicator: "% of regularly trafficked lanes designed for long-life".

V. Poor	Poor	Fair	Good	V. Good
0.33	0.67	0.00	0.00	0.00

- *Phase 1: Sustainability Planning* – In this phase, stakeholders collaborate to define the sustainability objectives and indicators applicable to the roadway project. Also, the benchmarks and importance of indicators applicable in each phase of project life cycle are also identified.
- *Phase 2: Sustainable Implementation* – When the project is implemented, best practices are applied, and the achieved level of performance values for each sustainability indicator can be logged and provided to the sustainability evaluation tool.

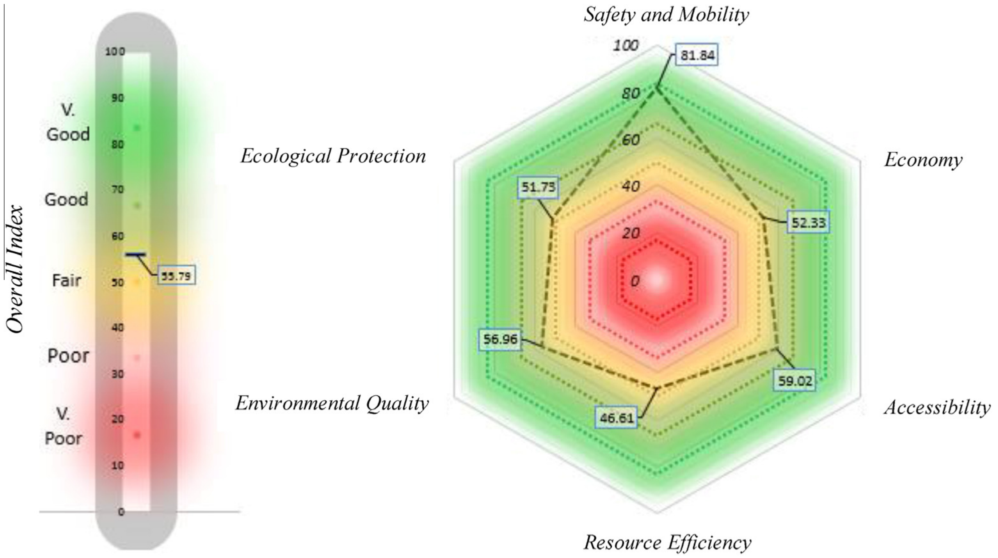


Figure 4. A vignette of Roadway Project Sustainometer.

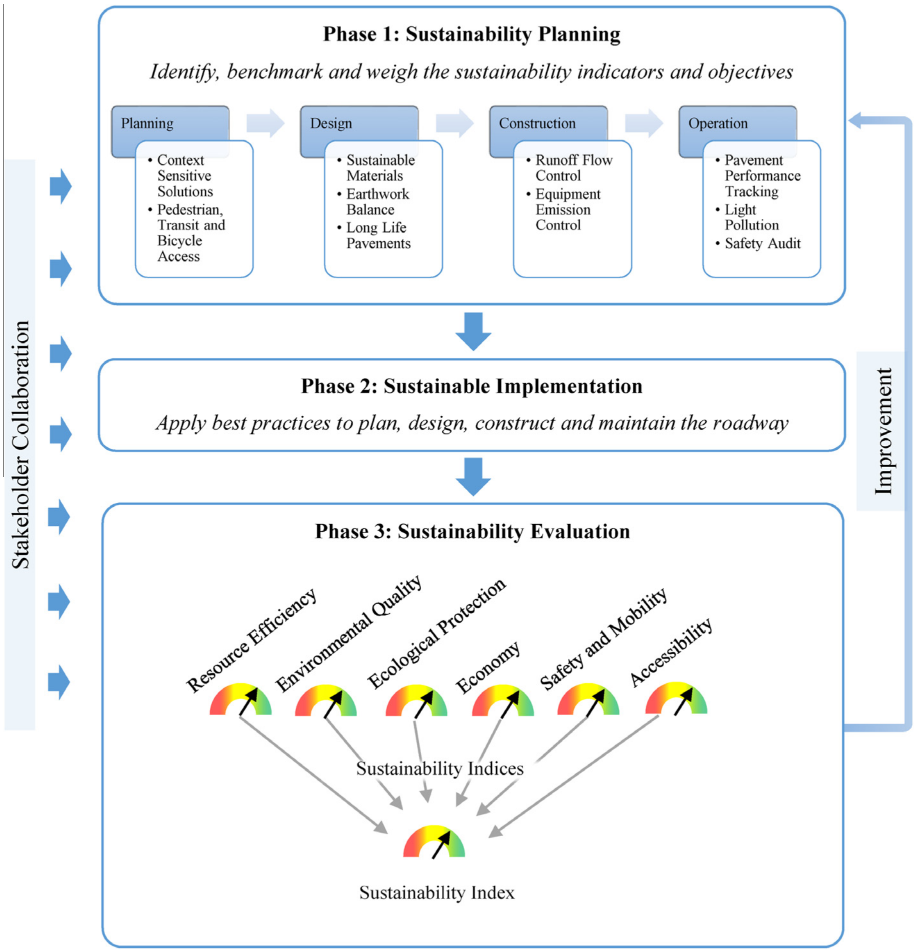


Figure 5. Conceptual demonstration of Green Proform application for the sustainability assessment of different lifecycle phases of a roadway project.

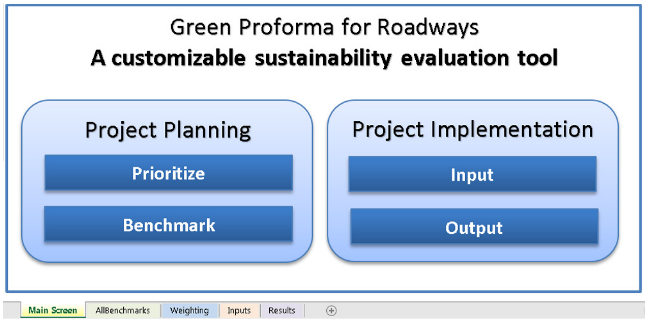
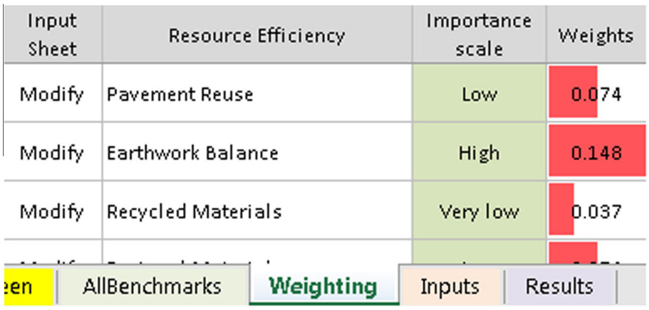
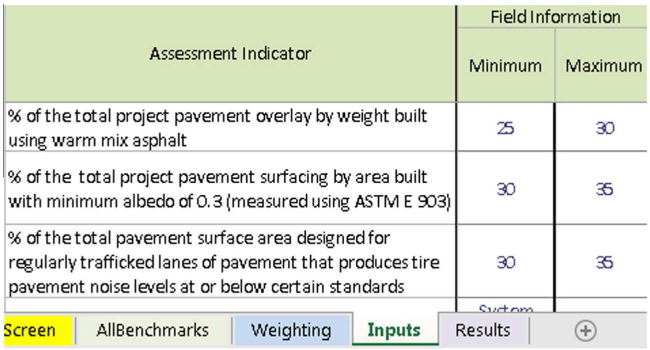


Figure 6. Main screen of Green Proforma.



Input Sheet	Resource Efficiency	Importance scale	Weights
Modify	Pavement Reuse	Low	0.074
Modify	Earthwork Balance	High	0.148
Modify	Recycled Materials	Very low	0.037

Figure 8. Prioritize best practices in Green Proforma.



Assessment Indicator	Field Information	
	Minimum	Maximum
% of the total project pavement overlay by weight built using warm mix asphalt	25	30
% of the total project pavement surfacing by area built with minimum albedo of 0.3 (measured using ASTM E 903)	30	35
% of the total pavement surface area designed for regularly trafficked lanes of pavement that produces tire pavement noise levels at or below certain standards	30	35

Figure 9. Input achieved best practices in Green Proforma.

- *Phase 3: Sustainability Evaluation* – Depending on the level of achieved indices, the decision-making team can review the cause of deficiencies in obtained index and underlying performance indices. Moreover, the learned lessons from the undertaken sustainable roadway project can be translated to improve the indicator parameters in Phase 1.

An Excel-based tool called the “Green Proforma for Roadway Projects” has been programed for practical application of the proposed sustainability assessment framework (see Figs. 6–10). Fig. 6 illustrates the main screen of the tool which shows sub-options for project planning and project implementation phase. During project planning, sustainability criteria is defined by providing benchmarks and weights of criteria via respective options to reach Excel interface as shown in Figs. 7 and 8. When the project is implemented, Fig. 9 illustrates the achieved level of performance for each criteria provided after the implementation of the project. Final output of the Green-performa for sustainability assessment of the roadway project under study is presented in Fig. 10.

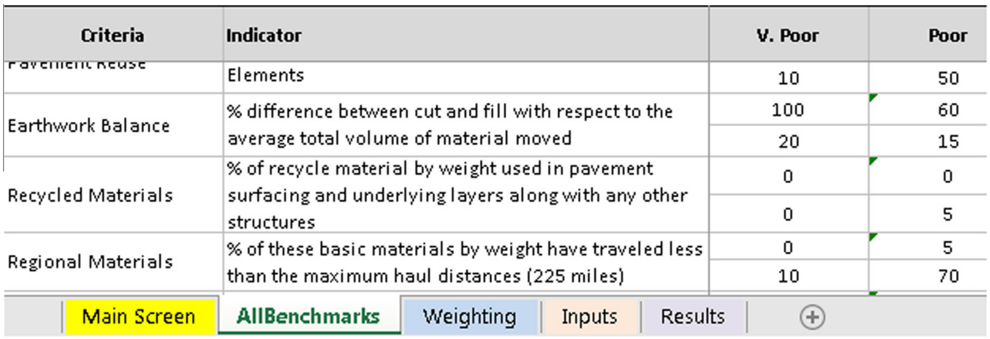
3. Results and discussions

3.1. Scenario analysis

Roadway projects vary significantly in scope due to several factors, e.g., the geographical location of the project, stakeholder’s priorities, environmental setting of the area, climatic conditions, etc. The Green Proforma enables the stakeholders to incorporate the expert judgment and regional constraints in the overall sustainability assessment processes. A scenario analysis has been performed in this research based on decision maker’s preferences on two different hypothetical scenarios (Fig. 11). The description of the scenarios along with the Green Proforma simulation results are discussed in the following paragraphs.

3.1.1. Scenario 1: ecocentric

Roadways passing through environmentally or ecologically sensitive zones that require higher attention to local geology, topography, and natural resources are considered as ‘ecocentric’, e.g. highways in hilly regions or heavily forested zones. In such cases, number of best practices related to the protection of natural laws are applicable as



Criteria	Indicator	V. Poor	Poor
Pavement Reuse	Elements	10	50
Earthwork Balance	% difference between cut and fill with respect to the average total volume of material moved	100	60
		20	15
Recycled Materials	% of recycle material by weight used in pavement surfacing and underlying layers along with any other structures	0	0
		0	5
Regional Materials	% of these basic materials by weight have traveled less than the maximum haul distances (225 miles)	0	5
		10	70

Figure 7. Benchmark best practices in Green Proforma.

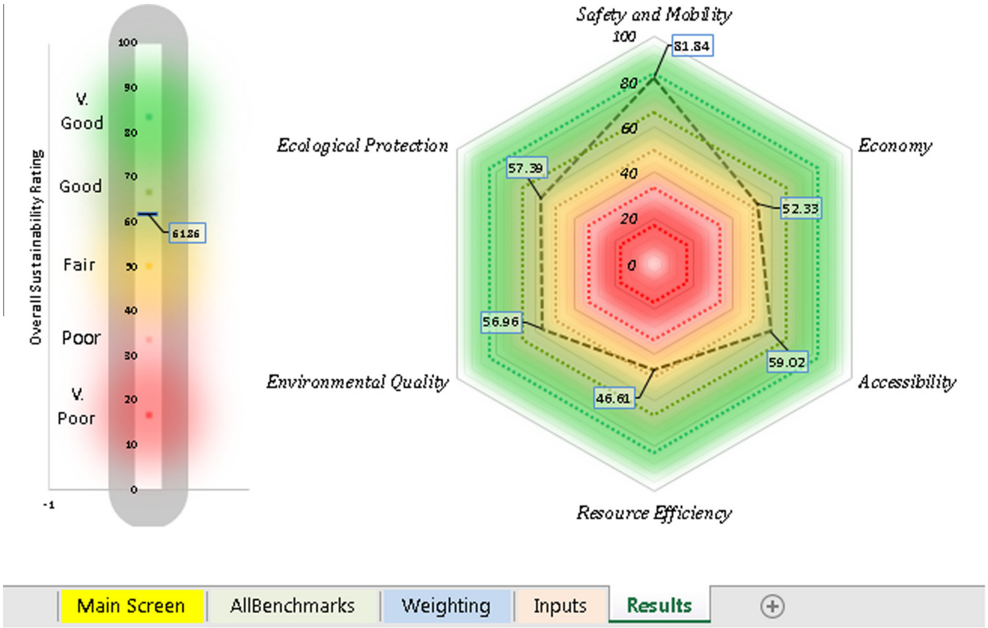


Figure 10. Output results in Green Proforma.

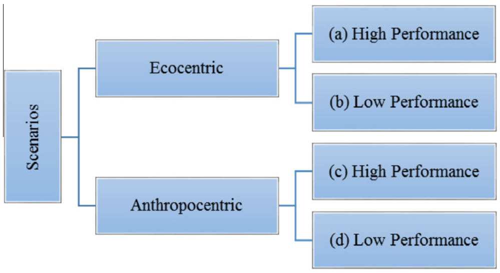


Figure 11. Scenarios evaluated in this study using Green Proforma.

compared to those that support human values e.g. provision of bike lanes might not be required, in contrast, ensuring ecological connectivity would be a vital factor to be considered.

3.1.2. Scenario 2: anthropocentric

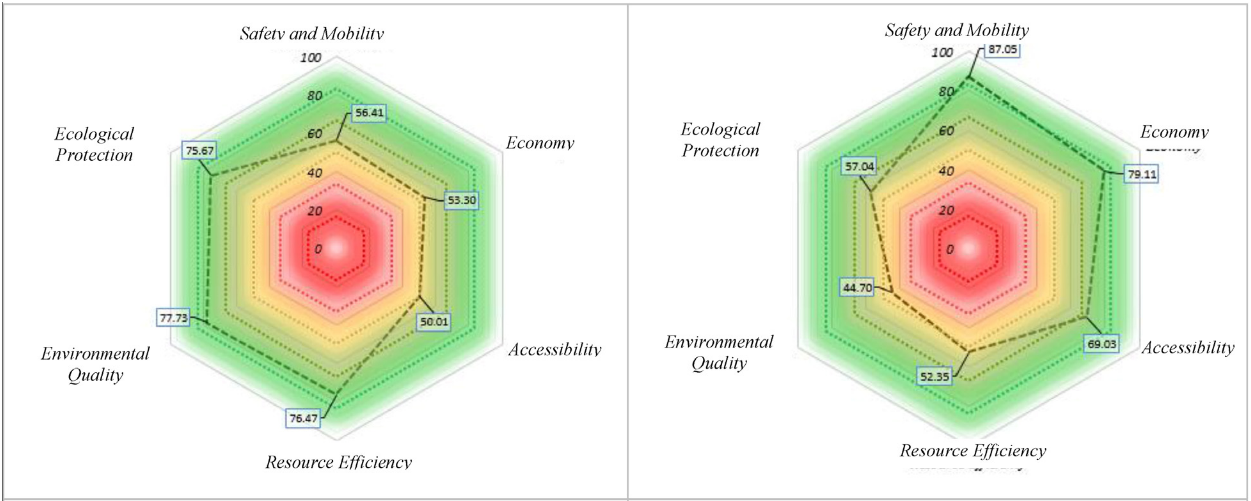
Roadway projects that require higher attention to societal benefits such as safety, economy, and accessibility are categorized as ‘anthropocentric’. Potential examples in this category can include urban roads such as locals and collectors. In such cases, more number of best practices supporting human values are applicable as compared to those that protect natural laws e.g. building infrastructure for ecological connectivity may not be practical; conversely, provision of bike lanes would be highly desirable.

Each of the above-mentioned scenarios has been further been subdivided into the following two performance levels which makes a total of four scenarios depending on the number of best practices implemented for a roadway project:

High-Performance – The roadway project adequately fulfills the indicators requiring higher attention.
Low-Performance – The roadway project does *not* fulfill the indicators requiring higher attention.

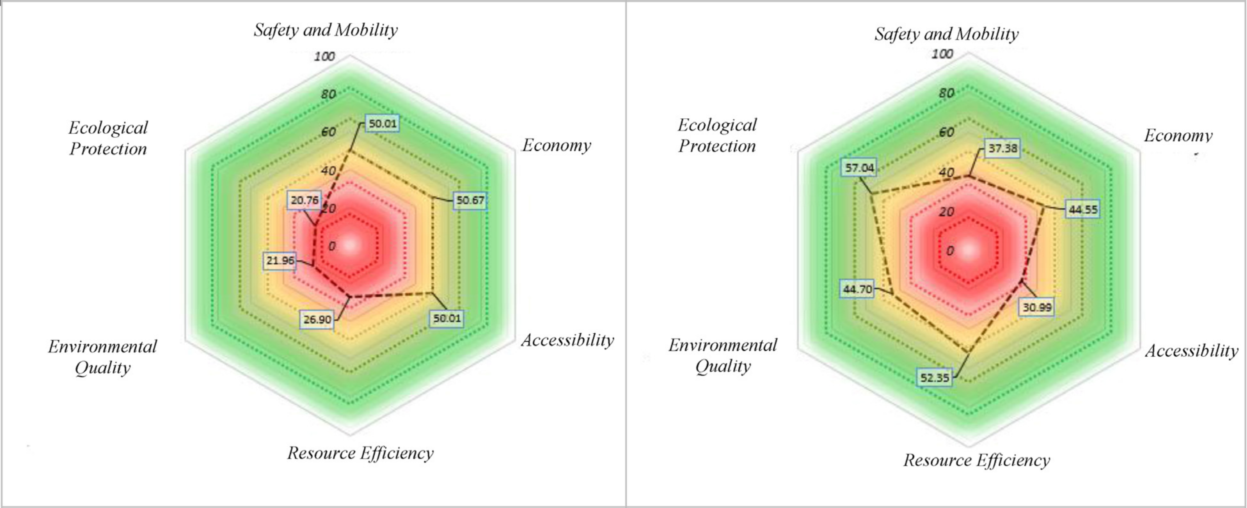
All scenarios (a–d) shown in Fig. 11 are simulated based on “reasonable” (i.e., best judged) values for the relevant indicators the results are shown in Fig. 12. Indicator benchmarks, weights, and inputs are provided to the Green Proforma to generate a radar chart for illustrating each scenario. The weights for each indicator and the benchmarks are assigned to each performance levels based on the sustainability points and associated performance levels provided in the Greenroads™ rating system (Muench et al., 2011). Indicator input values are assumed according to the case under consideration. For instance, in the high-performance ecocentric scenario, indicators relevant to the protection of natural laws are assigned values close to “good” and “very good” performance levels to develop the radar diagram.

The indices shown in radar diagram for each case can be aggregated to generate the overall sustainability index to present the holistic sustainability of the roadway infrastructure. For aggregation, it is important to determine the contribution or importance of individual objectives to overall roadway sustainability in the form of weights. Three types of weight distributions are assumed to evaluate their impact on the overall sustainability index value. These schemes depict the priority levels or decision-makers preference toward the importance of objectives supporting natural laws or human values. These schemes are characterized below:



(a) High-Performance Ecocentric Scenario

(c) High-Performance Anthropocentric Scenario



(b) Low-Performance Ecocentric Scenario

(d) Low-Performance Anthropocentric Scenario

Figure 12. Roadway scenario analysis results from Green Proforma.

- Pro-environment: 80% of weight distribution to the objectives related to natural laws.
- Pro-Socioeconomic: 80% of weight distribution to the objectives related to human values.
- Neutral: equal weight distribution to all the objectives.

Fig. 13 shows the aggregated sustainability index for each case based on decision makers' preference toward sustainability objectives. The summary of results presented in Table 4 illustrate that the change in overall sustainability level (based on the closeness of index values to the center of linguistic scales) with respect to the change in decision-makers attitude or preference for the sustainability objectives. Both the high and low-performance ecocentric case are rated as "*Fair*" by the pro-socioeconomic attitude of decision-maker (Table 4). However, the pro-environment attitude of the decision-makers changes the rating of the high-performance ecocentric case to "*Good*" and the rating of the low-performance ecocentric case to "*Poor*" sustainability levels. Certainly, the latter is more realistic. The change in decision-maker's attitude can alter the outcome by 15 units that is roughly equivalent to skipping one of the sustainability performance levels. Scenario analysis results reveal that the overall rating can vary to some extent depending on the experience and opinion of decision makers.

4. Summary and conclusions

A roadway sustainability assessment framework, has been developed based on fuzzy synthetic evaluation (FSE) technique. An Excel-based tool called Green Proforma is programed based on the framework to assist in the expert-based sustainability assessment through the project decision-making phases. The Green Proforma incorporates expert opinion to define imprecise benchmarks, imprecise inputs and different prioritization of indicators

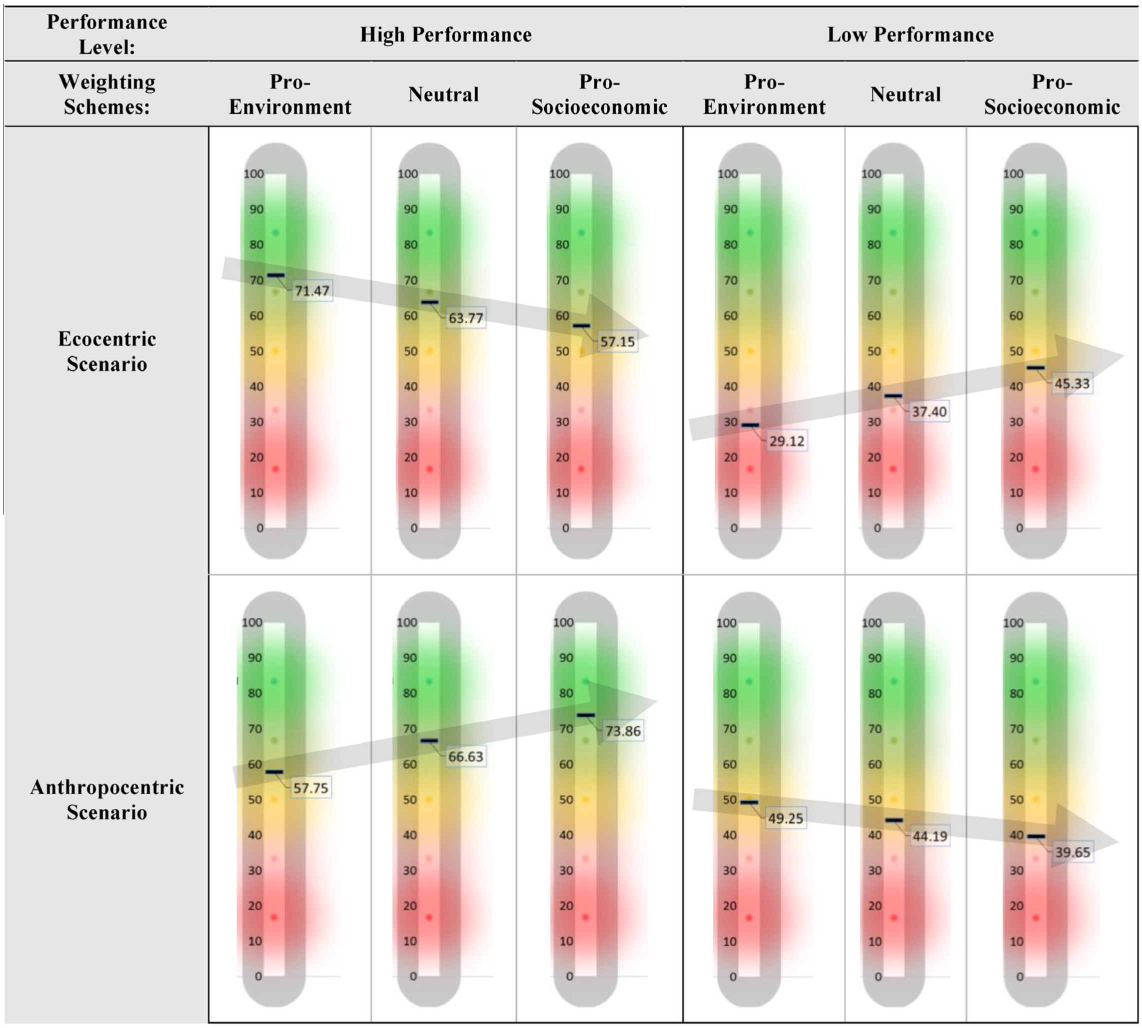


Figure 13. Overall indices for all the scenarios under each weighting scheme.

Table 4
Overall sustainability level based on the three weighting schemes.

Scenarios	Sustainability levels corresponding to the three weighting schemes		
	Pro-socioeconomic	Neutral	Pro-environment
High-performance ecocentric	Fair	Good	Good
Low-performance ecocentric	Fair	Poor	Poor
High-performance anthropocentric	Good	Good	Fair
Low-performance anthropocentric	Poor	Fair	Fair

and project sustainability objectives depending on stakeholder experience and keeping in view the constraints related to a given roadway project. The tool summarizes the sustainability assessment results in the form of a “Roadway Project Sustainometer” which illustrates the sustainability indices across the sustainability objectives and also shows the overall sustainability index of the project. As a demonstration of the importance of providing meaningful expert input in sustainability assessment process, scenario analysis has also been performed using the Green Proforma to evaluate the impact of the expert opinion on the model’s outputs.

The Green Proforma tool, using FSE technique, is fully capable of handling the uncertainties associated with imprecise benchmarks and inputs. The tool is customizable in benchmarking and prioritizing the sustainability of criteria. The customizability in prioritizing indicators and changing benchmarks should be transparent to all the project stakeholders. The requirement of time and resources from stakeholders is high as it is essential to provide meaningful inputs (benchmarks and weights related to multiple indicators requiring expertise from diverse backgrounds) for meaningful outputs from the sustainability assessment process.

Table A1
List of objectives, indicators, units and benchmarks based on Muench et al. (2011).

Objective	Indicator	Unit or measure	V. Poor	Poor	Fair	Good	V. Good
Accessibility	Context Sensitive Solutions	Consideration to Context Sensitive Solutions in the project design	No consideration	–	Partial consideration	–	Full consideration
	Pedestrian access	Develop new or existing facilities for enhancing pedestrian access	No consideration	–	Partial consideration	–	Full consideration
	Bicycle access	Develop new or existing facilities for enhancing bicycle access	No consideration	–	Partial consideration	–	Full consideration
	Transit access	Develop new or existing facilities for enhancing transit and HOV access	No consideration	–	Partial consideration	–	Full consideration
	Scenic views	Provide scenic access or viewpoints	No consideration	–	Partial consideration	–	Full consideration
	Cultural outreach	Install informational infrastructure to explain the site or direct roadway users to the site with special cultural value	No consideration	–	Partial consideration	–	Full consideration
Safety and mobility	Safety audit	Road safety audit (RSA) on the project roadway in accordance with FHWA's Road Safety Audit Guidelines	No consideration	–	Partial consideration	–	Full consideration
	Intelligent transportation systems	No. of Category where ITS is employed for 1 or more applications (categories available in rating system by Muench et al. (2011)	0 0	0 1	0 2	1 3	2 10
Economy	Contractor warranty	Years of Contractor warranty for constructed portions of pavements including surfacing and underlying layers	0 0	0 1	0 2	1 3	2 4
	Pavement performance tracking	Spatially located and correlation of data from construction quality and long term pavement performance measurements	No consideration	–	System needs improvement	–-	Effective system exists
	Long-Life pavement	% of the total new or reconstructed pavement surface area for regularly trafficked lanes of pavement to meet long life pavement design criteria	0 10	5 50	10 60	50 70	60 100
	Storm water cost analysis	Conduct Lifecycle Cost Analysis (LCCA) according to NCHRP Report 565: Evaluation of BMPs for highway runoff control guidelines	Not performed	–	Performed but no proper record or document exists	–	Complete application with adequate documentation
Resource efficiency	Quality management system	The prime contractor, design builder or construction management firm shall have a documented quality management system (QMS)	No consideration	–	Partial consideration	–	Full consideration
	Site recycling plan	Establish, implement, and maintain a formal Site recycling plan as part of the construction and demolition waste management plan (CWMP)	No consideration	–	Partial consideration	–	Full consideration
	Life cycle assessment (LCA)	Conduct a detailed process based lifecycle assessment (ISO LCA) or hybrid economic input output lifecycle assessment (Hybrid EIO) according to the ISO14040 standard frameworks for the final roadway design alternative	No consideration	–	Partial or incomplete application of LCA	–-	Full application
	Pavement reuse	% Reuse of existing pavement materials or structural elements	0 10	5 50	10 70	50 90	70 100
	Earthwork balance	% difference between cut and fill with respect to the average total volume of material moved	100 20	60 15	20 10	15 5	10 0
	Recycled materials	% of recycle material by weight used in pavement surfacing and underlying layers along with any other structures	0 0	0 5	0 10	5 50	10 100
	Regional materials	% of these basic materials by weight have traveled less than the maximum haul distances (225 miles)	0 10	5 70	10 80	70 90	80 100
	Energy efficiency	% of total luminaires installed on the project with energy efficient fixtures that are 2009 energy star compliant	0 1	0.5 20	1 40	20 80	40 100

Ecological protection	Environmental management system (EMS)	Existence of a formal environmental management process/system contractor/designer/management firm	No such system exists	–	Informal EMS exists	–	Organizations have ISO Certification & EMS meeting ISO requirements
	Runoff flow control	Ratio of post vs. pre - development stage volume/flow rate for 90th percentile average annual rainfall event	5 2	3.5 1	2 0.95	1 0.9	0.95 0
	Runoff quality	% of 90th percentile average annual rainfall event post-construction runoff volume – treated	0 0.4	0.2 0.7	0.4 0.8	0.7 0.9	0.8 1
	Site vegetation	Use non-invasive and native plants	No consideration	–	Partial fulfillment	–-	Full compliance
	Habitat restoration	% of required mitigation area restored	0 0.5	0.25 0.9	0.5 1	0.9 1.01	1 1.5
	Ecological connectivity	Development of recommended wildlife mobility and protective structures	No consideration	–	Partial consideration	–	Full consideration
	Light pollution	Provision of dark-sky compliant or equivalent lighting fixtures	No consideration	–	Partial consideration	–	Full consideration
	Permeable pavement	% of the 90th percentile average annual rainfall event post construction runoff volume treated to 25 mg/L concentration of total suspended solids (TSS) or less.	0 10	5 50	10 60	50 70	60 100
	Environmental training	Provide an environmental training plan that is customized to the project	No consideration	–	Partial consideration	–	Full consideration
Environmental quality	Warm Mix Asphalt (WMA)	% of the total project pavement (hot mix asphalt or Portland cement concrete) by weight built using WMA	0 10	5 50	10 60	50 70	60 100
	Cool pavement	% of the total project pavement surfacing by area built with minimum albedo of 0.3 (measured using ASTM E 903)	0 10	5 50	10 60	50 70	60 100
	Quiet pavement	% of the total regularly trafficked pavement surface area designed for to reduce tire pavement noise levels at or below certain standards	0 40	20 70	40 80	70 90	80 100
	Traffic emissions reduction	Use of congestion pricing and demonstrate the reduction in GHGs and pollutants	No consideration	–	Partial consideration	–	Full consideration
	Fossil fuel reduction	% Fossil fuel reduction by non road construction equipment (using biofuels or equivalent) by contractors	0 1	0.5 10	1 15	10 20	15 30
	Equipment emissions reduction	% of the non road construction equipment fleet operating hours for the project accomplished with integrated emission and fuel reduction technologies	0 10	5 20	10 50	20 60	50 100
	Paving emissions reduction	% of the hot mix asphalt (HMA) placed using a paver that is certified to have met National Institute for Occupational Safety and Health (NIOSH) emission guidelines	0 10	5 20	10 30	20 50	30 100
	Water tracking	Create a spreadsheet that records total water use during construction	No such activity considered	–	Irregular or incomplete monitoring	–	Full implementation and recording activities

Although, the Green Proforma offers a significant improvement over existing rating systems, the tool has some limitations e.g. capability to model the relationship of criteria to multiple objectives and lack of indicators that demonstrate long-term sustainability. These limitations can be addressed in further research to arrive at a more robust planning tool for sustainable roadway infrastructures.

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Appendix A

See Table A1.

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