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Simulating the impacts of policy scenarios on the sustainability performance of infrastructure projects

Yao Hong [a,*], Shen Liyin [a,1], Tan Yongtao [a,2], Hao Jianli [b,3]

[a] Department of Building & Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] Department of Architectural Science, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada M5B 2K3

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ABSTRACT

Sustainable development principles have been implemented in various sectors including the construction industry since it was published in the Brundtland Commission Report in 1987. In line with this development, implementation of infrastructure construction projects has been given particular attention as they have more significant impacts on the environment, society and economy. It is considered that proper development and operation of infrastructure projects such as highways can contribute significantly to the mission of sustainable development. However, there is little existing work to provide appropriate methods to assess the sustainability performance of infrastructure projects. The study described in this paper introduces a simulation model, using system dynamics principle, to evaluate the sustainability performance of highway infrastructure projects during the construction and operation stage. The study introduces the indicators which measure the sustainability performance of highway projects and identifies the dynamic factors affecting indicator performance by referring to the relevant feasibility studies of highway projects. A real highway project is presented to demonstrate the application of the simulation model in evaluating the sustainability performance of the project. The case study is used to explore the solutions for improving those poor sustainability performance areas through policy scenarios.

1. Introduction

Sustainable development is commonly defined as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs* [1]". As a result, infrastructure projects have been given particular attention as they have significant impact on the economy, social aspects and the environment. It is considered that the proper development and operation of infrastructure construction projects can contribute significantly to the mission of sustainable development.

Infrastructure projects include a wide range of construction works such as power plants, highways, railways, telecommunication facilities, provision of water and sanitation, and safe disposal of wastes. Developing infrastructure projects plays an essential role in economic and social developments. It is estimated that one percent increase in infrastructure stock is associated with one percent increase in GDP [2]. Kessides [3] pointed out that infrastructure projects contribute to economic growth, both through supply and demand channels by reducing costs of production, contributing to the diversification of the economy and providing access to the application of modern technology. Easterly and Rebelo [4] opined that investment in transportation and communication has a positive effect on economic growth. Esfahani and Ramirez [5] asserted that the contribution of infrastructure services is substantial to economic growth.

Noted, are other further studies on the significance of infrastructure provision to raise the quality of life and poverty reduction. A study by Kessides [3] suggests that infrastructure projects contribute towards raising the quality of life by creating amenities in the physical environment and by providing consumption goods (transport and communication services). Infrastructure projects are also important conditions for improving labor productivity and access to employment, and thus the capacity to earn future income and increasing consumer demands. In addition, a number of studies [6–8] pointed out the significant impact of infrastructure projects on poverty reduction through economic growth.

While infrastructure projects make significant contributions to economic and social development, they may cause undesirable consequences to the environment if they are not properly implemented. For example, power plants and vehicle emissions on roads are typical contributors to air pollution. Combustion of fossil fuels leads to greenhouse gas emissions. Overuse of water for irrigation (which accounts for about 90% of water withdrawal in most low-income countries) damages soil and severely restricts water availability for

* Corresponding author. Tel.: +852 2766 5828; fax: +852 2764 5131.
E-mail addresses: bsyao@polyu.edu.hk (H. Yao), bsshen@polyu.edu.hk (L. Shen), bstan@polyu.edu.hk (Y. Tan), janehao@ryerson.ca (J. Hao).
[1] Tel.: +852 2766 5805; fax: +852 2764 5131.
[2] Tel.: +852 2766 5828; fax: +852 2764 5131.
[3] Tel.: +1 416 9795000x4082.

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both industry and households. Some infrastructure investments, especially road construction, can put unspoiled natural resources at risk and threaten indigenous communities [2,9–11]. Therefore, in line with the promotion of sustainable development worldwide, it is considered important to be able to understand the performance of infrastructure works to economic, social and environmental aspects collectively. It becomes a pressing issue to find ways for gaining better sustainability performance from implementing infrastructure works which will remain extensive in the near future.

There are various traditional methods for project evaluation, including economic appraisal, environmental impact assessment, social impact assessment and life cycle analysis. However, these methods are usually applied to assess the performance of construction projects from the perspectives of economic, social and environmental dimensions respectively. The absence of an integrative approach has been leading to less consideration on the balance between economic, social and environmental performance when implementing an infrastructure project. In recent developments, several studies contributed in developing methodologies to incorporate project performance across economic, social and environmental dimensions collectively. One major weakness however in applying these methods is that they do not consider the impacts of dynamic interactions between various factors on project performance. In fact, it is essential to appreciate the dynamic impacts of various factors on project performance during the process of implementing projects, especially for those large-scale infrastructure projects with extensive investments and long period of construction and operation time. It is therefore the aim of this study to investigate an alternative project sustainability assessment approach which not only considers project performance across economic, social and environmental dimensions collectively, but also takes into account the impacts of the dynamic interactions of various factors on the project performance. This study will focus on the highway projects during construction and operation stages to illustrate the application of a simulation approach using system dynamics principle for evaluating sustainability performance of infrastructure projects.

2. Indicators for Measuring the Sustainability Performance

A number of studies have been conducted to examine the infrastructure project sustainability from different perspectives. For example, Colorni et al. [12] applied decision support system to assess the environmental impact of transport infrastructure. Tsunokawa and Hoban [13] introduced several methods in designing and executing effective environmental assessments to road projects from planning to construction to maintenance. Organization for Economic Co-operation and Development (OECD) [11] proposed a set of attributes to indicate the economic, environmental and social impacts caused by transport infrastructure. The study by Kennedy [14] described the environmental impacts associated with roads and the mitigation measures for reducing the magnitude of their effects. Belli et al. [15] presents an economic evaluation method for evaluating the economic benefits of transport projects. Shen et al. [16] developed a prototype model for accessing the sustainability of construction projects in life cycle based on system dynamics. A study by Ugwu and Haupt [17] proposed an indicator system for assessing the sustainability of a built infrastructure. Research efforts have also been given to examine the sustainability for different types of infrastructure, such as transport infrastructure, wastewater infrastructure, and energy infrastructure [18–20]. There are still other works studying the sustainability of infrastructure projects from different social groups [21,22]. However, it appears that these studies have some limitations in providing effective indicators for evaluating the sustainability performance of highway projects. This paper will formulate a list of key indicators for guiding the evaluation on sustainability performance of highway projects before the project is implemented.

The examination on the existing studies and feasibility study reports of highway projects leads to the formulation of a list of candidate indicators for measuring the sustainability performance of highway projects. To ensure the comprehensiveness and appropriateness of the identification of the indicators, two workshops were conducted in China. Construction professionals including directors and departmental managers in construction companies, consultants, as well as governmental officers concerned, were invited to comment on the comprehensiveness, suitability and clarity of individual indicators. As a result, a preliminary list of 33 indicators for measuring the sustainability performance of highway projects were formulated, as presented in Table 1.

To measure the relative significance of these 33 indicators, a questionnaire survey was therefore conducted in China to collect professional views on the levels of importance of indicators in terms of their contribution to project sustainability. The respondents were requested to rate the indicators according to a five point Likert scale based on their hands-on experience on project evaluation practice. The measurement of the Likert scale is translated as follows: 1 — not suitable, 2 — unimportant, 3 — common indicator, 4 — important, and 5 — most important. The questionnaire was piloted firstly in three cities in China: Beijing, Taiyuan and Shenzhen. Because no adverse comments were received from the interviewees, the questionnaire was taken as the final empirical questionnaire for the investigation. A total of 73 valid responses were received for analysis, and the overall response rate was about 30%. The 73 returned questionnaires consisted of 16 respondents from main contractors, 15 from client organizations, and 23 from consultants from various disciplines that

Table 1
Preliminary list of indicators for evaluating sustainability performance of highway projects and their relative significance.

Dimensions	Proposed indicators	Code	Mean	Standard deviation
Economic aspects	Market supply and demand analysis	I1	3.21	0.53
	Project budget	I2	3.17	0.67
	Project financing channels	I3	2.98	0.76
	Project investment planning	I4	2.82	0.65
	Life cycle cost	I5	4.35	0.52
	Life cycle benefit/profit	I6	4.35	0.52
	Financial net present value	I7	4.81	0.69
	Financial internal rate of return	I8	4.72	0.73
	Financial benefit–cost ratio	I9	4.32	0.62
	Payback period	I10	4.20	0.72
	Economic net present value	I11	4.67	0.68
	Economic internal rate of return	I12	4.20	0.71
	Economic benefit–cost ratio	I13	4.10	0.84
	Technical advantage of construction project	I14	2.78	0.87
	Reliable mobility	I15	3.48	0.76
Environmental aspects	Ecological effect evaluation of project	I16	4.25	0.79
	Air pollution	I17	4.72	0.56
	Noise emissions	I18	4.80	0.53
	Water quality (surface and groundwater)	I19	3.60	0.77
	Waste	I20	3.60	0.87
	Productive soil loss	I21	3.73	0.79
	Erosion	I22	3.93	0.77
	Soil contamination	I23	3.67	0.85
	Habitat loss and damage	I24	3.87	0.72
Social aspects	Location efficiency	I25	4.02	0.69
	Impacts of community development	I26	3.98	0.71
	Impacts on life standard	I27	3.65	0.81
	Impacts on historic, scientific, social and amenity values	I28	3.42	0.65
	Harmony between the project and various features of the landscape	I29	3.28	0.75
	Short-term health	I30	3.67	0.83
	Long-term health	I31	3.85	0.79
	Road safety	I32	4.87	0.68
	Job opportunities	I33	4.16	0.78

included architects, engineers, project managers and quantity surveyors. Nineteen respondents were from government officers who are responsible for project approval.

By feeding the survey results into software "PASW 17", the total score, mean and standard deviation of each indicator were generated. The key statistical results are summarized in Table 1.

Considering that grade 3 in the 5-point Likert scale implies the average value for acceptance of a suitable indicator, the indicators with a mean value exceeding or equal to 3.00 are treated as key indicators, and indicators with the mean value lower than 3.00 are discarded. It can be seen from Table 1 that 30 indicators highlighted by shade meet this criterion, and their standard deviation is small, showing that there is no significant difference among the respondents in their judgment on the significance of individual indicators. The 30 indicators in Table 1 are identified as key indicators for evaluating the sustainability performance of highway projects.

In order to confirm the validation of the calculated key indicators for measuring the sustainability performance of highway projects, a series of interviews were conducted in Beijing with 15 professionals from senior government officers responsible for road construction project approval, road contractors, road consultants and road clients. The interviews focused on the adequacy and suitability of the indicators. Feedbacks and suggestions were made by interviewees, which led to the modification of the selected key indicators. These suggestions contributed in the course of interviews and can be summarized as follows:

- The key indicators identified are suitable to evaluate the sustainability of highway projects.
- Indicators I1 and I15 can be grouped together, because reliable mobility reflects the situation of market supply and demand.
- Indicators I2 and I4 can be grouped together and can be embodied in Indicator I7.
- Indicator I2 is reflected at the level of implementing project, rather than at the level of evaluating the economic benefits of project, suggesting its deletion.
- Indicators I5 and I6 can be embodied in Indicator I7 and I9, therefore suggesting its deletion.
- Indicator I25 embodied the impacts of community development and the impacts on life standard from construction of highway projects, therefore suggesting the deletion of Indicator I26 and I27.
- Indicator I16 is too broad, and needs to be specified.

The suggestions from interviews provide useful reference for modifying the identified 30 key indicators. Based on the suggestions, the modified 23 key indicators for evaluating the sustainability performance of highway projects are produced, as shown in Table 2.

Developing a set of indicators is an indispensable aspect in evaluating the sustainability performance of highway projects. The 23 indicators are therefore established for evaluating the sustainability performance of highway projects. The assessment on the performance of these indicators can provide crucial information on judging the feasibility of a highway project for decision-making from the perspective of sustainable development. The results from examining these indicators in a particular highway project can provide an early indication of the weak areas in economic, social and environmental performance from implementing the project so that corrective methods can be adopted in advance. The establishment of the indicators also provides the essential basis for developing a dynamic evaluation model for evaluating the sustainability performance of highway projects which will be addressed in next section.

Table 2
Key indicators for evaluating the sustainability performance of highway projects.

Dimensions	Proposed indicators	Code
Economic aspects	Financial net present value	I1
	Financial internal rate of return	I2
	Financial benefit–cost ratio	I3
	Payback period	I4
	Economic net present value	I5
	Economic internal rate of return	I6
	Economic benefit–cost ratio	I7
	Reliable mobility	I8
Environmental aspects	Air pollution	I9
	Noise emissions	I10
	Water quality (surface and groundwater)	I11
	Waste	I12
	Productive soil loss	I13
	Erosion	I14
	Soil contamination	I15
	Habitat loss and damage	I16
Social aspects	Location efficiency	I17
	Impacts on historic, scientific, social and amenity values	I18
	Harmony between the project and various features of the landscape	I19
	Short-term health	I20
	Long-term health	I21
	Road safety	I22
	Job opportunities	I23

3. Simulation Model for Evaluating the Sustainability Performance of Highway Projects

Simulation using system dynamics principle is widely used to gain understanding of a system with complex, dynamic and nonlinearly interacting variables [16]. It can assist to understand the impact of various dynamic factors on the objectives defined in a system and has been proven effective and applied in structuring problem situations to provide understanding and, hence, appropriate solutions. For example, Love et al. [23] presented a framework using system dynamics for analyzing dynamic feedbacks in managing complex projects. Ford [24] identified various dynamic factors affecting project development process, which provides useful reference for improving the effectiveness of project development by properly responding to those major factors. By using the system dynamics method, Pena-Mora and Li [25] introduced a dynamic planning procedure for implementing design-and-build type construction projects. This procedure enables a dynamic plan that incorporates dynamic feedback and responds accordingly to the impact of various dynamics. Chritamara et al. [26] developed a model by using system dynamics principle for evaluating project management procedures and mitigating time and cost overruns.

System dynamics is used as a typical simulation technique for evaluating the decision-making performance. Dolol and Jaafarl [27] used the system dynamics approach as a simulation tool to establish the baseline value of a construction project. This approach provides an alternative method for optimizing investment decisions when project performance is assessed across the project life cycle. Shen et al. [16] developed a simulation model, using the system dynamics principle to assess the sustainable performance of projects, where three major attributes are used: the sustainability of economic development, the sustainability of social development, and the sustainability of environmental development. The development of using a system dynamics simulation approach in previous researches leads this study to the investigation on the use of this methodology in evaluating the sustainability performance of highway projects.

In the model developed by Shen et al. [16], the total sustainable performance value (TSPV) of a construction project in its life cycle is quantified by the following model.

$$\begin{cases} TSPV(t) = W_E\int_0^t I_E(t)dt + W_S\int_0^t I_S(t)dt + W_{En}\int_0^t I_{En}(t)dt \\ W_E + W_S + W_{En} = 1 \\ I_E, I_S, I_{En} \in [0, 100] \end{cases} \quad (1)$$

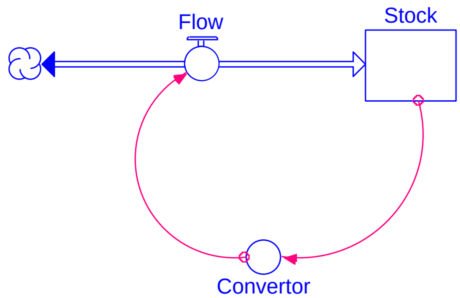

Fig. 1. A simple model of system dynamics [16].

where $I_E(t)$, $I_S(t)$ and $I_{En}(t)$ denote respectively the dynamic functions of generating economic impact, social impact and environmental impact from implementing construction projects. The values of the variables I_E, I_S and I_{En} are defined as impact values to *TSPV*, which are relative measures within the interval [0, 100]. Variables W_E, W_S *and* W_{En} denote respectively the weights of economic impact, social impact and environmental impact on the *TSPV*.

In using system dynamics principle, there are four elements: (a) stock; (b) flow; (c) converter; and (d) connector, as shown in Fig. 1. A stock collects all those in-flows and also serves as the source from which out-flows come. A flow serves as a vehicle to deliver resources to or drain resources from the stock. The value of a flow can be positive or negative. A positive flow is an in-flow and will fill the stock, and a negative flow is an outflow draining the stock. A convertor has a utilitarian role in selecting proper values and functions of parameters in the model. The connector is an information transmitter connecting different elements. A complex system has more connectors [16].

In Fig. 1, the volume of stock will change at different points of time as both in-flows and out-flows will be generated as time goes on. The relationship between the stock and flow is established as follows [16]:

$$\begin{cases} Stock(t) = Stock(t-dt) + Flow(dt) \\ Stock = \int Flow(dt) \end{cases} \tag{2}$$

By applying the parameters designed in model (1), a prototype model of *TSPV* for a highway project can be developed as shown in Fig. 2.

In Fig. 2, the stock (*TSPV*) collects three types of flow, namely, economic impact (I_E), social impact (I_S) and environmental impacts (I_{En}). They can be measured by the indicators identified in Section 2 of this paper. The three convertors (W_E, W_{En} and W_s) can adjust the volume of the three types of flow. The adjustment implies that efforts can be devoted to improve I_E, I_S and I_{En}. It can be seen that feedback loops exist from the stock *TSPV* to the three attributing factors (economic dynamic factors, social dynamic factors and environmental dynamic factors), and from *TSPV* to three flows I_E, $I_{En,}$ and I_S. The feedback loops are used to indicate that while *TSPV* is determined by the three types of flow, the volume of *TSPV* will also influence the flow in return. For example, when *TSPV* is large, the flow can be adjusted by a reduction of the three types of flow. Thus the values of I_E, I_S and I_{En} are changeable by applying adjustment measures (i.e. the convertors "?" in Fig. 2). By this feedback mechanism, the existing volume of *TSPV* and other dynamic factors will decide the value of adjustment. The application of the TSPV prototype model (1) needs the provision of values for various parameters. These parameters include I_E, I_S, I_{En}, environmental factor, economic factors, social factors, W_E, W_S and W_{En}.

The parameters I_E, I_S and I_{En} are functions of time and indicate that the implementation of a construction project has different social, economic and environmental impacts at different stages of construction and operation. The values of I_E, I_S and I_{En} are determined respectively by economically related dynamic factors, social dynamic factors and environmental dynamic factors. These 23 indicators embodied in the model are subject to the influence of various dynamics factors, and interact with each other. For example, the indicator "Financial net present value" is determined respectively by cash inflow and cash outflow. The cash outflow over the period of construction and operation are comprised of four items including construction costs, operation management and maintenance costs, sale taxes and income taxes while the cash inflows are comprised of three items, i.e., the sum of toll incomes from vehicles, residual values and other incomes. The dynamic factors affecting the noise emissions during the operation stage of the highway projects attribute to vehicular characters, road surface, road geometry and spatial relationships etc. However, the control measures to higher noise emission level will increase construction costs, and in turn influence the performance value of indicator "Financial net present value", and furthermore affect the total sustainability performance value (TSPV). Tables 3–5 provide the summary of the major dynamic factors to each of the three sample indicators. Considering too many dynamic factors affecting both the individual indicator performance and the complex

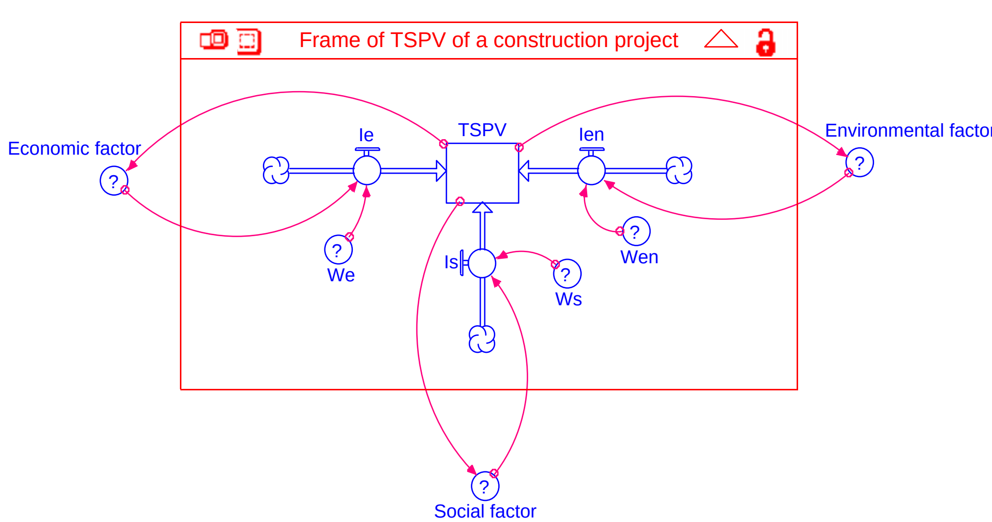

Fig. 2. A prototype model of TSPV using system dynamics [16].

Table 3
The major dynamic factors contributing to the performance of the indicator “Financial net present value (I1)”.

• Financial cash inflows	• A rate at which the level of routine maintenance costs will change in the next unit time (dt)
• Road toll incomes from various types of vehicles	• The cost of routine maintenance per kilometer
• Residual value of a highway project	• A percentage determined by decision makers at which the annual routine maintenance costs will be increased yearly
• Other incomes	• The rate at which the operation management costs will change in the next unit time (dt)
• The length of road	• The first year of operation management costs determined by decision makers based on the project's specific operation management condition.
• Road toll standard	• The percentage at which the operation management costs will be increased yearly
• Practical vehicle volumes for the various types of vehicles	• Annual sales tax rate
• Forecasted day vehicle volumes for various types of vehicles	• Income tax rate
• Impacts of price strategy on the forecasted day vehicle volumes for various types of vehicles	• Annual project's profits
• Price strategy of road toll	• Annual extracted depreciation expenses
• The impact of price strategy on road toll standard	• Annual loan interest payment
• Total construction costs of a highway project	• The project's operation duration
• Estimated percentage of total construction costs for the residual value	• Accumulated principal borrowed in a given year
• Financial cash outflows	• Annual loan interest rate
• Annual construction costs	• Annual principal borrowed
• Annual sum of operation management and maintenance costs	• Annual principal payment
• Annual sale taxes	• Annual principal payment
• Annual income taxes	• Project client's equity fund
• The ratio of construction cost arranged yearly during the period of construction	• Other money sources annually
• Operation and maintenance costs	• Annual financial net cash flow
• Periodic maintenance costs in a given year	• The discount factor
• Routine maintenance costs annually	• The selected per-period rate of discount
• Operation management costs annually	• The present values of the financial net cash flow in each year
• The impact of road design standard on routine and periodic maintenance costs	• The impact of mitigation measures on total construction costs

relationships among the factors, three major indicators are selected for analysis, including “Financial net present value”, “Noise emissions” and “Job opportunities”.

The weighting factors W_E, W_S and W_{En}, are assumed as constants decided by decision makers. Different decision makers may allocate weighting values differently by considering the characteristics of different types of projects. For example, when the environmental impact is considered more important, the weight of environmental impact, W_{En}, will be more than 1/3. In another application, all the three weighting factors may be considered equally important and be given the same value (namely, 1/3). Furthermore, the relationships between system elements including stock, flow, convertors and connectors need to be established in a specific application of *TSPV* prototype.

By incorporating these parameters into the TSPV prototype mode, the simulation model for evaluating the sustainability performance of highway projects is formulated, as shown in Fig. 3. The model delineates three subsystems used for measuring the sustainability performance of highway projects. The interactions occur not only between subsystems but also within each subsystem. The analysis procedures and calculation methods for the dynamic model have been effectively formulated in the software “iThink” and the use of the software will be highlighted by a case study in next section.

4. Model Validation and a Base Case Simulation

4.1. Model Validation

Model validation is a crucial process in building confidence in the soundness and usefulness of a model [28]. The usual process by which this confidence is generated is called ‘validation’ [29]. Coyle [30] outlined the main tests which should be used to validate a system dynamic model. These tests include:

- Verification tests, which are concerned with verifying that the structure and parameters of the real system have been correctly transcribed into the model.
- Validation tests, which are concerned with demonstrating that the model actually generates the same type of behavior that would be expected from the real system.
- Legitimation tests, which are applied to determine that the model follows the laws of system structure or any generally accepted rules.

Table 4
The major dynamic factors contributing to the performance of the indicator “Noise emissions (I10)”.

• The total sound level when the plants and equipment operate	
• The impact of site operation practice on noise emissions	• The designed vehicle speed of a highway project
• Mitigation measures for controlling noise emissions during the construction	• Road grade design
• The noise emissions of large-sized, medium-sized, and small-sized vehicles, respectively	• Road surface design
• The daily traffic volumes of large-sized, medium-sized, and small-sized vehicles, respectively	• Distance attenuation factors
• The average hourly speed of large-sized, medium-sized, and small-sized vehicles respectively	• Mitigation measures for controlling noise emissions during the operation

Table 5
The major dynamic factors contributing to the performance of the indicator "Job Opportunities (I23)".

• The number of direct employment opportunities	
• The number of indirect employment opportunities	• Direct employment effect per unit investment
• Total construction costs	• Indirect employment effect per unit investment

In line with these principles, a series of validations are carried out to the system dynamic model introduced in this paper, and the validation results are shown as follows:

- The simulation model developed corresponds to the statement of problem which is to evaluate the sustainability performance of highway project.
- A close inspection of the equations for the development of simulation models reveals that the direction of the relationships in model equations matches the direction of the relationships in stock and flow diagrams.
- Every equation in the simulation model is in dimensional consistency.
- The model does not produce any unrealistic values. This is checked by printing out a graph of the main variables in the model over the simulation run; showing the variables by running the model reflects the realistic value.
- The value produced for main variables in the simulation model when their inputs take on extreme values is consistent with the values which should be assigned.
- The behavior of the model is what we expect it to have.

In the application of the system dynamics approach, a specific problem will be firstly identified and then the dynamic characteristics of the problem will be described. A reference mode is used to specify and characterize a problem dynamically. A reference mode, either historically observed or hypothesized, is graphical or in the form of verbal descriptions showing the structure or development of the problem with reference to the time dimension [31]. According to the study by Shen et al. [32], the SPV (Sustainability Performance Value) of a specific project is considered as a distribution as shown in Fig. 4(a), while the distribution of SPV in reality can be various and much more complicated. As shown in Fig. 4(a), during the construction stage (Tc starting from t_1 to t_2), consumption of resources and environmental problems will contribute negatively to the environment, and social and economic aspects, and the degree of negative impact will be aggravated during the construction process. Therefore, SPV is considered gradually to reduce during the initial period of the process. However, the SPV value will gradually go up when the construction process approaches completion as it will have less environmental effects and provide more employment. The formats of the environmental impact from a construction project during the construction stage are various, and a quadratic curve is proposed for describing such impact. When the construction of a project is completed, the project moves to the operation stage. During the project operation stage (from t_2 to t_3 in Fig. 4(a)), both economic and social benefits will be gradually obtained. Adverse environmental impacts will also be identified and corrected accordingly, thus, a gradual linear line SPV is suggested to reflect the improvement of the project's contribution to sustainable development. With the operation of a project, operation conditions and outcomes will generally remain consistent. Operation activities will be organized to aim to achieve the social and economic objectives of the project, and more attention will also be given to environmental protection. Therefore, SPV is considered constant in this period. TSPV can be obtained by conducting a definite integral of the function SPV during the construction and operation stages. The distribution of TSPV is graphically shown in Fig. 4(b).

It can be seen from Fig. 5 that the model for calculating the total sustainability performance value (TSPV) from a practical case replicates the reference mode of total sustainability performance value.

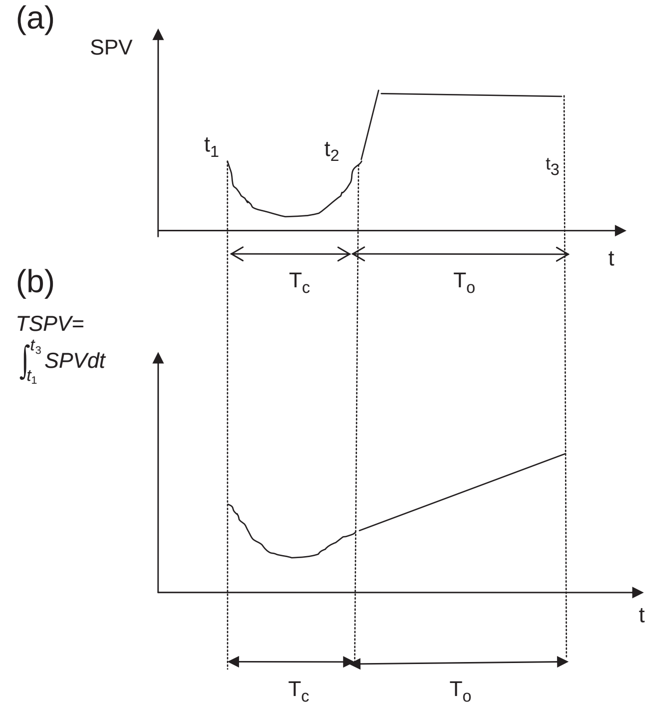

Fig. 4. The distribution of SPV and the reference mode of TSPV of a construction project [32].

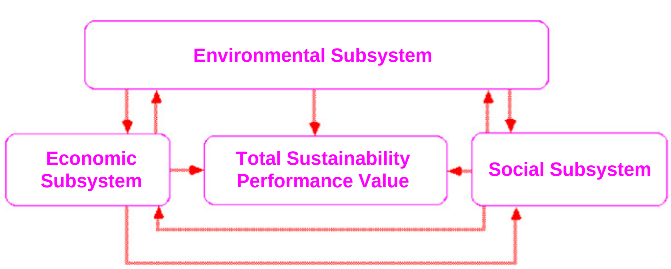

Fig. 3. A dynamic model for evaluating the sustainability performance of highway projects.

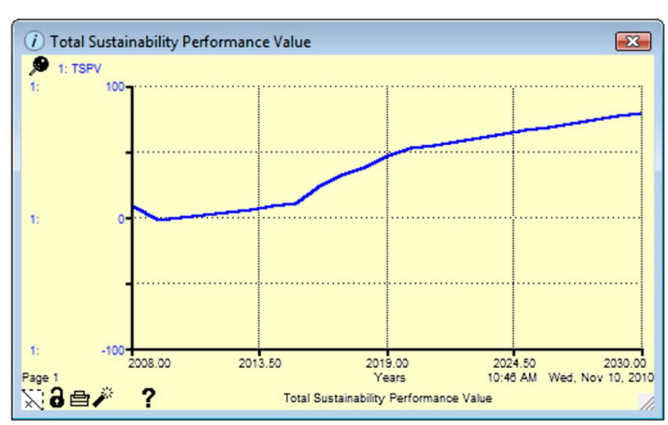

Fig. 5. The simulation of total sustainability performance value (TSPV).

4.2. Base Case Simulation

After various model validations are conducted, a real case study is used to illustrate the applicability of the dynamic simulation evaluation model in measuring project sustainability performance for different project alternatives. This will be the base case, when compared to other policy scenarios in the following sections.

The investigated highway project is located in a provincial capital city in China. The highway passes through several counties which are important energy bases and heavy-chemistry bases with high population density. There is an increasing pressure on this city's congested transport system. Transport has been a major bottleneck for the city's economic and social development. Lack of transport infrastructure has severely hindered the city's development. The construction of this highway is expected to relieve congestion, in order to facilitate the economic and social development. Currently, the project is under construction.

A proposal is put forward to build a 41.95 km four-lane expressway between county A and county B. The total investment is expected to be RMB 1189.73 (m).The initial year of construction is in 2008 and the estimated life time ends in 2030. Construction period is 3 years and operation life is planned at 20 years.

The data are collected mainly from the feasibility study of the highway project. With the support of the "iThink" package, the dynamic evaluation model can simulate the total sustainability performance value for the design options. Table 6 shows the simulation results of the 23 indicator performance values and total sustainability performance values.

5. Policy Scenarios

Using the dynamic evaluation model, the project decision-makers can not only evaluate the project's total sustainability performance, but also identify the poor areas of sustainability performance by examining the performance values of the 23 indicators. The results of this examination can lead to the adoption of further improvement actions.

By examining the simulated performance value of the 23 indicators in Table 6, it can be found that the following indicators have much better performance values:

I1 (Financial net present value)
I3 (Financial benefit-cost ratio)
I5 (Economic net present value)
I6 (Economic internal rate of return)
I7 (Economic benefit–cost ratio)
I12 (Waste)
I22 (Road safety)

The performance of the indicators I10 "Noise emissions", and I23 "Job opportunities" are poor with the performance value of less than 70. Here, the indicator I10 "Noise emissions" is taken as an example to illustrate how improvement can be obtained by using the principle of interactions between dynamic factors. This example can be extended to other indicators such as "Job opportunities" for similar analysis on performance improvement.

Considering that it is difficult to be exhaustive in testing all possible parameter changes, we just select several parameters to demonstrate the improvement process. Four policy scenarios are used for improving the sustainability performance in poor areas: (1) adopting the mitigation measures for controlling the noise emissions; (2) adopting a high-price strategy in collecting the road toll; (3) adopting a low-price strategy in collecting the road toll; and (4) adopting a combination of high-price strategy and mitigation measures for controlling the noise emissions. The results from adopting these four types of policies are explained as follows.

5.1. Simulation 1: Policy Scenario (1)

Policy 1 is used to test the performance value changes of noise emissions during the period of operation and its impacts on the total sustainability performance value when emission mitigation measures are adopted.

In this scenario, the assumption is that the mitigation measure of vegetation screen method is applied. The forecasted noise emissions after adopting the mitigation measures will be reduced by 5 dB noise level from the base value. Correspondingly, relevant costs will be incurred when mitigation measures are adopted. The change of total construction costs in this case due to the adopting of the mitigation measure is projected to increase to RMB 1 million according to empirical estimation from other highway projects. By running the simulation with the new policy, the performance value of noise emissions (I10) has reached to 64.71 after adopting the mitigation measures and total sustainability performance value (TSPV) is 80.95 as shown in Table 7(a).

It can be seen from Table 7(a) that, after the adoption of the policy, the total sustainability performance value has increased by 0.48 from 80.47 (see Table 6) to 80.95 (see Table 7(a)). From Table 7(a), it can also be seen that the performance value of noise emissions has increased to 64.71, a 10.77 increase in comparison with the original value 53.94 in Table 6 before the adoption of the policy.

5.2. Simulation 2: Policy Scenario (2)

Policy 2 is to test the performance value changes of noise emissions during the period of operation when a high-price strategy for the road toll is adopted. The impacts of this policy on the total sustainability performance value will be assessed.

According to the demand theory in economics, consumers will buy more goods when price decreases, and less when price increases. This principle is adopted in this scenario simulation. In using the "iThink" package, the logical functional relationship between price strategy and its impacts on daily traffic volumes is converted into graphical relationship, as shown in Fig. 6. Further, the noise emissions can therefore be adjusted by modified traffic volumes.

The graphical function expresses that when a high price strategy is adopted, the daily traffic volumes will reduce, and vice versa. The horizontal axis (i.e. "price strategy") in Fig. 6 is referred to as the independent variable, and the vertical axis (i.e. "price effect on traffic volumes") is referred to as the dependent variable. The value of "price effect on traffic volume" depends on the value of "price strategy". The coordinates of the first point (1, 1.983) indicates that when the very low price strategy denoted by 1 is adopted, the impact coefficient for modifying daily traffic volumes of the base case is 1.983. Here, the price strategy is divided into 5 levels. 1 denotes the very low price strategy, 2 for a low-price strategy, 3 for a moderate price strategy, 4 for a high-price strategy and 5 for a very high price strategy. Respectively, their impact coefficient for modifying daily traffic volumes of the base case is provided in the graphical relationship. When a high price strategy is adopted, the daily traffic volumes of the base case are modified by multiplying them with the coefficient 0.731.

This relationship shown in Fig. 6 can be changed based on the practical relationships. The current relation in Fig. 6 is just expressed by the logical relationships between price strategy and its impact on the daily traffic volumes because of the lack of data exactly describing the relations between these two variables currently. By running the evaluation model with the new policy, the simulation on the total sustainability performance values (TSPV) and the performance value of the noise emissions (I10) can be undertaken, and the simulation results are presented in Table 7(b).

Table 6
The simulation results of 23 indicator performance values and total sustainability performance value (TSPV).

Indicator Performance Value
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Table 6 (Indicator Performance Value)

Years	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	Final
I1	0.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	15.55	61.33	63.16	65.34	68.87	72.40	75.92	79.42	82.88	86.29	89.52	92.71
I2	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27	87.27
I3	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	4.78	22.16	38.69	54.28	62.37	65.33	68.65	73.41	77.55	81.18	84.37	87.15	89.60	91.50	93.20
I4	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00	74.00
I5	60.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	14.14	46.08	62.09	65.75	68.52	71.82	74.94	77.89	80.65	83.24	85.63	87.82	89.85	91.71
I6	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00
I7	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00	16.06	34.65	52.35	62.44	66.68	69.65	73.34	76.82	80.07	83.11	85.95	88.56	90.95	93.14	95.15
I8	0.00	0.00	0.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00	80.00
I9	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I10	0.00	2.78	5.56	8.33	10.97	13.58	16.17	18.72	21.23	23.72	26.18	28.61	31.01	33.38	35.74	38.07	40.39	42.68	44.96	47.22	49.48	51.72	53.94
I11	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I12	0.00	2.61	5.22	7.83	12.17	16.52	20.87	25.22	29.57	33.91	38.26	42.61	46.96	51.30	55.65	60.00	64.35	68.70	73.04	77.39	81.74	86.09	90.43
I13	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I14	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I15	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I16	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I17	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I18	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I19	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I20	0.00	2.61	5.22	7.83	11.30	14.78	18.26	21.74	25.22	28.70	32.17	35.65	39.13	42.61	46.09	49.57	53.04	56.52	60.00	63.48	66.96	70.43	73.91
I21	0.00	3.48	6.96	10.43	13.91	17.39	20.87	24.35	27.83	31.30	34.78	38.26	41.74	45.22	48.70	52.17	55.65	59.13	62.61	66.09	69.57	73.04	76.52
I22	0.00	3.48	6.96	10.43	14.78	19.13	23.48	27.83	32.17	36.52	40.87	45.22	49.57	53.91	58.26	62.61	66.96	71.30	75.65	80.00	84.35	88.70	93.04
I23	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65	64.65
TSPV	8.38	-1.96	0.09	2.14	4.33	6.53	8.72	10.91	23.62	32.96	38.30	47.97	53.10	55.78	58.56	61.45	64.30	67.10	69.85	72.57	75.25	77.87	80.47

Table 7
Total sustainability performance value (TSPV) and performance value of noise emissions (I10).

Years	(a) Policy scenario (1) TSPV	(a) I10	(b) Policy scenario (2) TSPV	(b) I10	(c) Policy scenario (3) TSPV	(c) I10	(d) Policy scenario (4) TSPV	(d) I10
2008	8.48	0.00	8.38	0.00	8.38	0.00	8.48	0.00
2009	-1.85	2.78	-1.96	2.78	-1.96	2.78	-1.85	2.78
2010	0.20	5.56	0.09	5.56	0.09	5.56	0.20	5.56
2011	2.24	8.33	2.14	8.33	2.14	8.33	2.24	8.33
2012	4.46	11.47	4.33	11.05	4.32	10.72	4.46	11.55
2013	6.68	14.58	6.53	13.75	6.50	13.05	6.68	14.74
2014	8.89	17.67	8.73	16.43	8.69	15.35	8.90	17.92
2015	11.10	20.73	10.93	19.08	10.87	17.61	11.12	21.07
2016	23.71	23.78	23.42	21.72	23.99	19.84	18.86	24.21
2017	33.06	26.80	32.74	24.34	33.36	22.03	32.84	27.32
2018	38.40	29.81	38.07	26.94	38.72	24.18	38.17	30.42
2019	42.59	32.79	42.23	29.51	50.37	26.30	42.34	33.50
2020	53.33	35.76	53.02	32.06	53.23	28.39	52.96	36.57
2021	56.04	38.71	55.71	34.59	55.92	30.46	55.95	39.62
2022	58.85	41.64	58.48	37.09	58.70	32.49	58.75	42.65
2023	61.76	44.57	61.37	39.58	61.60	34.51	61.66	45.68
2024	64.63	47.48	64.21	42.04	64.44	36.50	64.52	48.69
2025	67.45	50.37	67.01	44.50	67.25	38.47	67.34	51.69
2026	70.23	53.26	69.76	46.93	70.01	40.43	70.12	54.68
2027	72.98	56.14	72.48	49.35	72.73	42.36	72.86	57.66
2028	75.68	59.00	75.15	51.76	75.41	44.29	75.56	60.63
2029	78.33	61.86	77.77	54.16	78.03	46.19	78.20	63.60
Final	80.95	64.71	80.37	56.54	80.63	48.09	80.82	66.56

It can be seen from Table 7(b) that the total sustainability performance value has decreased by 0.1 from 80.47 (see Table 6) to 80.37 (see Table 7(b)). From Table 7(b), it can also be seen that the performance value of noise emissions has increased to 56.54, a 2.6 increase in comparison with the original value 53.94 in Table 6 before the adoption of the policy.

5.3. Simulation 3: Policy Scenario (3)

Policy 3 is to test what would happen to the performance value of noise emissions when a low-price strategy for the road toll is adopted and its impacts on the total sustainability performance value.

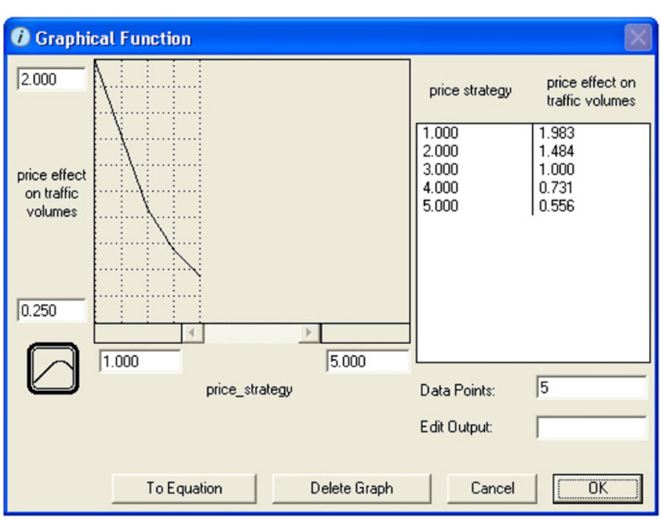

Fig. 6. A graphical function describing the impact of price strategy on traffic volumes.

The level of noise emissions after adopting policy 3 can be calculated by considering the changes of daily traffic volumes which are affected by road price strategy. When a low-price strategy is adopted, the daily traffic volumes of the base case are modified by multiplying them with the impact coefficient 1.484, referring to Fig. 6. By running the evaluation model with the new policy, the performance value of the total sustainability performance values (TSPV) and noise emissions (I10) can be obtained, as presented in Table 7(c).

Comparing the results of the two indicator performance values with ones shown in Table 6, it can be seen from Table 7(c) that the total sustainability performance value has increased to 80.63, an increase of 0.16 from the original value 80.47 which was gained before the adoption of the new policy. However, the performance value of noise emissions has reduced to 48.09, decreased by 5.85 in comparing with the original value 53.94 in Table 6 before the adoption of the new policy. Therefore, this policy does not contribute to the performance improvement for noise emission level.

5.4. Simulation 4: Policy Scenario (4)

This simulation is to show how the performance of the noise emissions and the total sustainability performance value change when a combined policy is adopted. In other words, the examination of the effects of a combination of changes in the two variables on the behavior of the system is given. It can be expected that the noise emission level and its impacts on the total sustainability performance value will change when two variables (price strategy and mitigation measures) change together. The price strategy is the adoption of a high price policy, and the mitigation measure is the adoption of the vegetation screen method.

When a high-price strategy is adopted, the daily traffic volumes of the base case is modified by multiplying them with the coefficient 0.731, referring to Fig. 6. The forecasted noise emissions after adopting the mitigation measures will reduce the noise level from its base value by 5 dB. On the other hand, relevant costs will be incurred due to the adoption of mitigation measures, and the total construction costs will increase by RMB 1 million. The detailed illustrations of this scenario simulation are similar to "Simulation 1: policy scenario (1)" presented before in this section. Accordingly, simulation by using policy 4 was undertaken. As for the results, the performance values of noise emissions (I10) and the total sustainability performance value (TSPV) have changed due to the adoption of policy 4, as shown in Table 7(d).

It can be seen from Table 7(d) that the total sustainability performance value has increased by 0.35 from 80.47 (see Table 6) to 80.82 (see Table 7(d)). From Table 7(d), it can also be seen that the performance value of noise emissions have increased to 66.56, a 12.62 increase in comparison with the original value 53.94 in Table 6 before the adoption of the new policy.

Therefore, it can be seen that, from the four policy scenarios, policy 1 and policy 4 can make better contributions to the improvement of both noise emission level and total project sustainability performance.

6. Conclusions

The introduction of a dynamic model to support the evaluation of sustainability performance in highway projects presents a new methodology for investigating the contribution of construction to the mission of sustainable development. The identification and selection of the indicators for evaluating the sustainability performance of infrastructure projects such as highway projects are multiple and lie across three major dimensions which include economic, environmental and social. Through an extensive and in-depth review of the literature, and interview discussions with professionals, 23 key indicators are selected for evaluating sustainability performance. These indicators contribute collectively to the measurement of the sustainability performance of highway projects. The establishment of the indicators provides an important basis for understanding the sustainability performance of infrastructure projects such as highway projects.

The study explores the principles of the system dynamics approach in evaluating the sustainability performance of highway infrastructure projects through investigating the dynamic factors affecting the performance of indicators. The dynamic approach captures a holistic view of the evaluation system being assessed, integrating collectively three dimensions of sustainable development principles i.e., economic, environmental and social development sustainability. The approach can support analysis of the impact of dynamic interactions between various factors on the sustainability performance. An understanding of this impact allows project decision-makers to identify how a particular level of project sustainability performance is obtained. Improvements in sustainability performance can therefore be made if it is unsatisfactory by adjusting some dynamic factors. The adoption of this approach in the discipline is of innovation, and contributes to the development of research in the field of sustainability performance evaluation.

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