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A Comprehensive Life-Cycle Cost Analysis Approach Developed for Steel Bridge Deck Pavement Schemes

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Abstract: This study aims to evaluate the economy of a steel bridge deck pavement scheme (SBDPS) using a comprehensive life-cycle cost (LCC) analysis approach. The SBDPS are divided into the “epoxy asphalt concrete system” (EA system) and “Gussasphalt concrete system” (GA system) according to the difference in the material in the lower layer of the SBDPS. A targeted LCC checklist, including manager cost and user cost was proposed, and a Markov-based approach was applied to establish a life-cycle performance model with clear probability characteristics for SBDPS. Representative traffic conditions were designed using a uniform design method, and the LCC of SBDPS under representative traffic conditions and different credibility (construction quality as a random factor) was compared. The reliability of the LCC analysis approach was verified based on the uncertainty analysis method. Based on an expert-scoring approach, a user cost weight was obtained to ensure it is considered reasonably in the LCC analysis. Compared with the cumulative traffic volume, the cumulative equivalent single axle loads (CESAL) have a closer relationship with the LCC. The GA system has better LCC when the CESAL is less, while the EA system is just the opposite. The breaking point of CESAL for the LCC of the EA system and the GA system is 15 million times. The LCC analysis of SBDPS should consider the influence of random factors such as construction quality. The comprehensive LCC analysis approach in this paper can provide suggestions for bridge-management departments to make a reasonable selection on SBDPS.

Keywords: steel bridge deck pavement; life-cycle; economy analysis; manager cost; user cost



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1. Introduction

The steel bridge has experienced rapid development over the last two decades because of its excellent ability to cross rivers in China. The steel bridge deck pavement on steel bridge decks for protection and the satisfaction of traffic requirements is an important structural layer of a steel bridge [1]. Due to the requirements of the bridge's self-weight load, the thickness of steel bridge deck pavement is limited to 5.0–7.5 cm, which leads to the steel bridge deck pavement being just like a coating of the steel bridge. Generally, steel bridge deck pavement has higher requirements for material performance compared to common road pavement. With a significant amount of research and practice effort, Gussasphalt (GA) concrete, epoxy asphalt (EA) concrete, and stone matrix asphalt (SMA) concrete are the most widely used pavement materials for steel bridge decks. EA concrete is a thermo-set material that uses a reaction-curing material of epoxy asphalt that will not melt or soften under 70 °C and has proven to be a super-durable surfacing material for heavy-duty traffic and extremely high temperatures. GA concrete is a type of asphalt mixture that is paved at high temperatures (200–240 °C) without roller compaction because of its self-consolidation. It features near zero air-void content, good corrosion resistance, strong deformability, and superior cracking resistance. SMA concrete is a type of asphalt mixture that contains a gap-graded aggregate with a high content of coarse aggregate and a rich mixture of asphalt cement, filler, and additives that show high antiskid performance [2–4].

A desirable steel bridge deck pavement scheme (SBDPS) should have high ductility to adjust to the deformation of steel decks, sufficient failure strength to prevent cracks, sufficient high-temperature performance, and imperviousness to protect the steel deck [5]. However, it is difficult for a single type of asphalt concrete to satisfy all the requirements, so SBDPS often adopt a double-layer structure that can combine the advantages of pavement materials and reduce the impact of the materials' weaknesses. The lower layer of a SBDPS serves as the direct protective layer for the steel plate, the load-bearing structural layer, and the transition layer of the pavement structure to connect the steel bridge decks and the upper layer of the SBDPS, the pros and cons of which directly determine the performance of the SBDPS [6]. As of today, EA concrete and GA concrete are mostly used in the lower layer of SBDPS. For convenience, the SBDPS in this paper are divided into the "EA system" and "GA system", according to the difference between the material of the lower layer of SBDPS.

It is attributed to the combined action of external factors, such as traffic load, water, and temperature changes, that the force and deformation of SBDPS are extremely complex. Distresses in SBDPS inevitably occur during its service, which can increase maintenance costs and vehicle-operating costs. It will also produce a huge amount of indirect loss for managers (toll loss) and user-time delay cost due to great disturbances to traffic during the maintenance process, especially for bridges located in the traffic throat. However, the bridge-management department that decides the choice of SBDPS may pay more attention to the cost that is more closely related to themselves, especially the initial construction cost in the current stage [7,8]. Therefore, it is necessary to provide an effective analysis method for bridge-management departments to consider, not only the initial construction cost, but also other costs during the whole service process, when deciding which SBDPS to choose.

The life-cycle assessment methodology has recently been identified as the most effective tool for measuring and comparing the environmental and economic performances of road pavements throughout their whole design life [9,10]. Life-cycle economic analysis is a method of economic budgeting and comparison during the life-cycle from engineering construction to demolition. The basic idea of life-cycle economic analysis is to consider not only the initial construction cost but also the maintenance cost, residual value, user cost (mainly including fuel consumption cost, wheel consumption cost, warranty cost, and accident cost), and other costs that should be taken into consideration during the service period [11,12]. At present, a relatively mature life-cycle economy analysis framework for road pavement schemes has been formed, and a life-cycle economic analysis of pavement structure has been applied to research into road pavement scheme comparison and selection, maintenance decision-making, limited capital allocation, and so on [13–16].

However, there are few studies on the life-cycle economic analysis for SBDPS. Zhang et al. [7] tried to obtain the LCC of three kinds of SBDPS. BaEk et al. [8] executed LCC analysis by mentioning case studies of SMA, GA, and PSMA pavements. However, the LCC checklist of the SBDPS adopted in the above studies is not comprehensive compared to road engineering. Besides, the performance models of the SBDPS have not been established for the above research. The performance models of SBDPS are not only directly related to the operating costs of vehicles but also trigger the need for maintenance, which leads to maintenance costs, indirect losses for managers, and traffic delay costs for users. Therefore, obtaining a reasonable performance model is the key and necessary step for life-cycle economic analysis of SBDPS. Current researchers mainly establish performance models of SBDPS through indoor tests, numerical simulations, full-scale accelerated loading tests, etc. [17–19]. Nevertheless, existing research on performance models are difficult to apply to the life-cycle economic analysis of SBDPS, because the highly deterministic environmental and traffic conditions during the tests and numerical simulations are quite different from conditions during actual engineering projects, and the impact of construction quality on the performance of SBDPS must be considered. Due to the special materials and complex construction process, the construction quality of SBDPS is more prone to uncertainty. The uncertainty of SBDPS cannot be completely controlled during the construction process

or perfected after construction, because it is difficult for the construction quality of the newly built pavement structure to show differences only through inspection indicators such as anti-skid, *IRI*, etc. The current methods used to establish performance models in civil engineering mainly include the Markov method, linear mixed models, machine learning, soft computing, the GA-BP neural network, and so on [20–24]. Considering that the principle of the state frequency conversion of the Markov method can better fit the performance change trend of SBDPS [25], performance data during the life-cycle should be obtained by investigating actual engineering projects, and a life-cycle Markov performance model of SBDPS with clear probability characteristics, considering the construction quality as a random factor, should be established.

In summary, a mature life-cycle economy analysis framework for road pavement scheme has been formed, but there are few comprehensive *LCC* analyses of SBDPS. Besides, a reasonable performance model for SBDPS has not been established for the *LCC* analysis of SBDPS. Considering the large difference between mechanical behavior and different maintenance management modes between the road pavement scheme and SBDPS, a comprehensive life-cycle economic analysis approach developed for SBDPS was proposed based on the existing *LCC* analysis framework for road pavement schemes. By proposing a targeted *LCC* checklist based on the structural and management characteristics of SBDPS, establishing a life-cycle Markov performance model of SBDPS with clear probability characteristics first, and, comparing the *LCC* of SBDPS under representative traffic conditions and different credibility (construction quality as a random factor), the research results can provide a basis for bridge-management departments to consider not only initial construction costs but also other costs during the whole service process and make a reasonable selection on SBDPS for different traffic conditions.

2. *LCC* Checklist of SBDPS

According to the difference in costs, the *LCC* checklist of SBDPS, including manager cost and user cost phases, was proposed as shown in Figure 1.

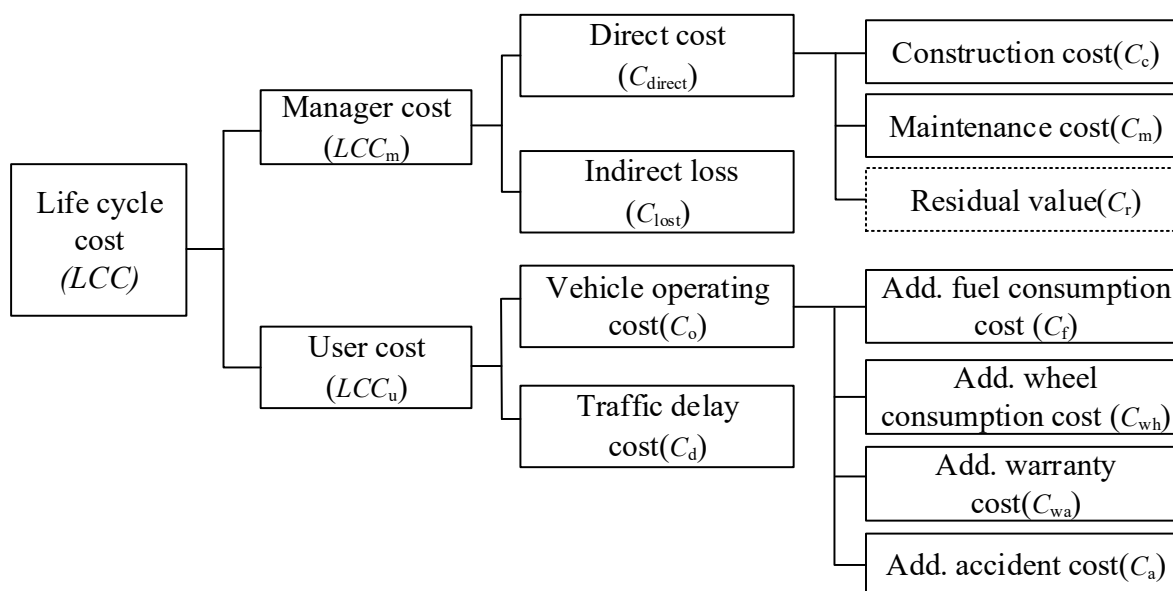


Figure 1. *LCC* checklist of SBDPS (Add. = additional).

2.1. Manager Cost Phase

Manager costs, including direct costs and indirect losses, are the costs paid by bridge-management departments. Direct costs are the costs directly paid by the bridge-management department and caused by construction and maintenance. Indirect loss refers to the loss of tolls caused by traffic blockages due to maintenance for the bridge

open to traffic. According to the literature [26], manager costs can be calculated by the following formula:

$$LCC_m = C_{\text{direct}} + C_{\text{lost}} \quad (1)$$

$$C_{\text{direct}} = C_c + C_m - C_r \quad (2)$$

where, LCC_m represents the manager costs; C_{direct} represents the direct costs; C_{lost} represents the indirect losses; C_c represents the construction costs; C_m represents the maintenance costs; and C_r represents the residual value.

2.1.1. Construction Cost

The construction costs of different pavement systems are different because the price of materials used for SBDPS is not stable, and the costs of equipment and labor for different construction teams are not the same. Therefore, the unit reference price per square meter of different pavement schemes can be obtained through investigations in the following context, and the construction cost can be obtained by multiplying the unit reference price per square meter by the total area of the SBDPS.

2.1.2. Maintenance Cost

Due to varying maintenance needs during the entire service life, it is not possible to achieve an accurate estimate of the maintenance cost of SBDPS. Based on the measurement rationale of maintenance costs, maintenance methods can be divided into daily maintenance and medium maintenance, and medium maintenance is carried out as needed. Daily maintenance cost can be obtained by multiplying the C_c and the daily maintenance rate α obtained by referring to the actual value of similar schemes. If needed, the medium maintenance cost can be obtained by multiplying the amount of maintenance and a single maintenance cost obtained by referring to the actual value of similar projects. The amount of medium maintenance can be calculated as follows.

Step 1: Select the performance index representative of the conditions of the SBDPS and construct a performance model of the SBDPS to obtain the attenuation law of the performance index.

Step 2: Set the maintenance threshold of the performance index. When the performance index decays below the threshold, increase the maintenance number once and adjust the performance model of the SBDPS by restoring a certain value according to the maintenance effect.

Step 3: Cycle step 1 and step 2, and count the amount of medium maintenance required during the analysis period.

2.1.3. Residual Value

In addition, since the life of the SBDPS at the end of the analysis period has not completely ended, the pavement structure still has a certain service capacity, so its remaining service capacity should be converted to economic value. The economic value of the remaining SBDPS service capacity at the end of the analysis period is called the residual value, which needs to be deducted when calculating the construction cost. According to the literature [25], the residual value can be calculated as shown in the following Formula (3):

$$C_r = C_c \times \frac{SDPQI_{\text{end}} - SDPQI_{\text{min}}}{SDPQI_{\text{max}} - SDPQI_{\text{min}}} \quad (3)$$

where, $SDPQI_{\text{end}}$ represents the performance index of SBDPS at the end of the analysis period, $SDPQI_{\text{max}}$ represents the performance index of SBDPS when construction is completed, generally taken as 100; and $SDPQI_{\text{min}}$ represents the lowest performance index of the SBDPS.

Due to the unique engineering materials, pavement structure, and mechanical properties of the SBDPS, the $SDPQI$ calculated, as shown in Formula (4), is chosen as the performance index of SBDPS [25].

$$SDPQI = 0.18 \times SDCCI + 0.21 \times SDPCI + 0.18 \times SDVDI + 0.17 \times SDSRI + 0.13 \times SDACI + 0.13 \times SDPPCI \quad (4)$$

where, *SDCCI* represents the crack condition index of the SBDPS; *SDPCI* represents the damage condition index of the SBDPS; *SDVDI* represents the vertical deformation index of the SBDPS; *SDSRI* represents the antiskid performance index of the SBDPS; *SDACI* represents the bonding condition index of the SBDPS; and *SDPPCI* represents the repair condition index of the SBDPS.

2.1.4. Indirect Loss

For toll bridges, there is a close connection between the indirect loss to the management department and the traffic flow of the bridge. Maintenance will bring loss of traffic flow, which leads to economic losses. To quantify the loss, it is firstly necessary to estimate the capacity of the bridge based on the theory of traffic flow. Secondly, the disturbance in traffic flow can be calculated according to the length of the maintenance work area, the operation time, and other parameters. Finally, indirect loss can be calculated by multiplying the traffic flow loss and the unit price of the toll, as shown in Formula (5) according to the literature [27].

$$C_{\text{lost}} = \sum_k Q_{\text{lost}}^k \times F \quad (5)$$

where, Q_{lost}^k represents the traffic flow loss caused by the k -th maintenance behavior, which can be calculated based on the research results of the “Life-cycle Cost Analysis in Pavement Design” [12]; F represents the unit price of tolls (yuan/pcu); pcu represents the passenger car unit.

2.2. User Cost Phase

During the service of the SBDPS, the deterioration of surface flatness results in additional vehicle fuel consumption, tire consumption, mechanical maintenance, and accident cost for users, as well as economic loss due to traffic delays caused by maintenance. Therefore, user costs, composed of vehicle operating costs and traffic delay costs, mainly refer to the economic loss of the users and are an indirect reflection of users’ satisfaction with travel quality.

2.2.1. Vehicle Operating Cost

There is different fuel consumption, tire wear, and damage to mechanical structures when vehicles run on different pavement surfaces. In addition, traffic accidents happen more often on surfaces with low flatness and a low friction coefficient. The vehicle operating cost, composed of additional fuel consumption cost (C_f), additional wheel consumption cost (C_{wh}), additional warranty cost (C_{wa}), and additional accident cost (C_a), can be calculated as shown in the following formula according to the literature [27]:

$$\begin{aligned} C_o &= C_f + C_t + C_v + C_a \\ &= 365 \times AADT \times \left(\sum_i \frac{P_F \times F_c^i \times L \times T}{1000} \times P_i + \sum_i \frac{P_T \times T_c^i \times L \times T}{1000} \times P_i + \sum_i \frac{P_v \times P_c^i \times L \times T}{1000} \times P_i \right) \\ &\quad + P_A \times AR \times L \times T \end{aligned} \quad (6)$$

$$F_c^i = a_1^i + b_1^i IRI, \quad T_c^i = a_2^i + b_2^i IRI \quad (7)$$

$$P_c^i = \begin{cases} a_3^i \times (e^{b_3^i IRI} - 1) \times CKM_i^{k_i} & \text{(for small vehicles and big vehicles)} \\ CKM_i^{k_i} \times a_3^i \times (1 + b_3^i \times IRI) & \text{(for heavy vehicles)} \end{cases} \quad (8)$$

$$AR = 2.955 + 0.292AADT + 0.0069s - 0.004SDSRI - 0.004SDPCI \quad (9)$$

where, C_o represents vehicle operating cost; P_i ($i = 1, 2, 3$) represents the proportion of the i -th model (respectively small vehicles, large vehicles, and heavy vehicles); $AADT$

represents average daily traffic volume (10^4 pcu/day); P_F represents the price of gasoline (yuan/L); P_T^i represents the unit price of the i -th tires (yuan/unit); P_V^i represents the price of the i -th vehicle (yuan/pcu); P_A represents the average cost of accidents (10^4 yuan per case); L represents the length of the road section (m); T represents the analysis period (years); F_c^i represents the fuel consumption of the i -th vehicle per thousand vehicles (L/km); T_c^i represents the tire consumption of the i -th vehicle per thousand vehicles (unit/km); P_c^i represents the ratio of maintenance cost to the price of new vehicles of the i -th vehicle per thousand vehicles (/km); AR represents the annual average number of accidents (/km); IRI represents the international roughness index (m/km); a_j^i, b_j^i ($j = 1, 2, 3$) represents the fitting coefficient, which is taken according to the literature [27]; k_i represents the vehicle age index; CKM_i represents the vehicle age (10^4 km); and s represents the average longitudinal slope of the road section (%).

2.2.2. Traffic Delay Cost

When vehicles pass through the maintenance area, the additional travel time will increase, due to the traffic delay, resulting in traffic delay costs that are mainly divided into low-speed costs and queuing costs. Low-speed costs mainly comprise more time wasted than in normal traffic conditions, resulting in economic loss to drivers and passengers, due to the reduction in the level of service for the maintenance area. The queuing cost is mainly the economic loss to drivers and passengers caused by queuing behavior due to insufficient capacity of the maintenance area. The traffic delay cost can be calculated as shown in the following formula according to the literature [28,29]:

$$C_D = AADT \sum_i P_i \times P_D^i \times (D_m + D_q) \quad (10)$$

$$D_m = L_{wz}(1/V_{wz} - 1/V_{nm}), D_q = L_q(1/V_q - 1/V_{nm}) \quad (11)$$

where, C_D represents vehicle delay cost (yuan); P_D^i represents the i -th model's time cost (h); D_m represents low-speed delay time (h); D_q represents queuing delay time (h); L_{wz} represents work area length, equal to the length of the road section (km); V_{wz} represents vehicle speed in the work area (km/h); V_{nm} represents vehicle speed under normal traffic conditions (km/h); L_q represents the length of the queue (km), obtained by multiplying the number of queuing vehicles by the length of the vehicles; and V_q represents the queue dissipating speed (km/h).

All the above speed parameters can be selected according to the provisions in the "Code for Design of Highway Routes" (JTG D20) [28] and the "Code for Design of Urban Road Engineering" (CJJ 37) [29], according to the level of service on the lane.

3. LCC Analysis Model of SBDPS

3.1. SBDPS Data in China

From the above, it is also necessary to specify the values of dynamic parameters, such as $SDPQI$, IRI , $SDSRI$, and $SDPCI$, at different stages of the life-cycle, in addition to the fixed parameters, such as the unit price per square pavement, daily maintenance rate, oil price, tire price, vehicle price, time cost, etc.

To clarify the fixed and dynamic parameters, six steel bridges using the EA system and the GA system in different locations that had served, for more than five years, in the midstream and downstream of the Yangtze River in China, were chosen as investigation samples in this study, and an investigation about their initial construction cost, daily inspection data, and maintenance records was made. Basic information from the investigation is shown in Table 1.

Table 1. Basic information from the investigation.

Sample Number	Location	Construction Time (Year)	Traffic Characteristics		Medium Maintenance Records	
			Current Daily Traffic (Vehicles)	Ratio of Big and Heavy Vehicles	Time	Repair Form
EA-1	Jiangsu Province	2001	Around 70,000	Around 40%	13th year 15th year	Centralized repair
EA-2	Hubei Province	2009	Around 50,000	Around 50%	-	-
EA-3	Hubei Province	2010	Around 20,000	Around 30%	9th year	Centralized repair
GA-1	Chongqing Province	2007	Around 80,000	<10%	9th year	Seal cover
GA-2	Jiangsu Province	2012	Around 25,000	Around 20%	5th year	Partial seal cover
GA-3	Anhui Province	2013	Around 40,000	Around 30%	5th year	Seal cover

3.2. Input Parameter of LCC Model

3.2.1. Fixed Parameters

Through the investigation, the specific value of each fixed parameter was obtained as shown in Table 2. Because the same amount of money has different values at different times, when performing present value analysis, it is necessary to convert the cost incurred at different times into the net present value of the base year through the discount rate. The discount rate in this article is 4%.

Table 2. Fixed parameters of LCC.

Item		Value	Unit	Notes
Analysis period		10	Years	-
Discount rate		4	%	-
Toll		10	yuan/pcu	Converted into small vehicles
Fuel price		6.68	yuan/L	-
Loss for every accident		4.5	10 ⁴ yuan	-
Size of steel-deck	Length	1000	m	Road section
	Width	33	m	-
	Lanes	6	-	In both direction
	Average grade	3	%	-
Construction cost	GA SYSTEM	1100	yuan/m ²	-
	EA SYSTEM	1500		
Residual value	$SDPQI_{\min}$ [25]	40		
Rate of daily maintenance	GA SYSTEM	2	%	-
	EA SYSTEM	1.50		
Threshold of repairing	GA SYSTEM	70	-	$SDPQI$
	EA SYSTEM			
Cost of repairing	GA SYSTEM	70	yuan/m ²	Coating Repairing
	EA SYSTEM	50		
Work zone	Lane closed	2	-	every time
	Closed period	7	Days	-
Price of wheels	For small vehicles	403	yuan	-
	For big vehicles	1535		
	For heavy vehicles	2168		
Price of vehicles	For small vehicles	14.46	10 ⁴ yuan	-
	For big vehicles	15.12		
	For heavy vehicles	33		
Age of vehicles	For small vehicles [27]	27.5	10 ⁴ km	-
	For big vehicles [27]	35		
	For heavy vehicles [27]	25		
Age index of vehicles	For small vehicles [27]	0.308	-	-
	For big vehicles [27]	0.483		
	For heavy vehicles [27]	0.371		
Value of passengers' time	For small vehicles [30]	32.78	yuan/h	-
	For big vehicles [30]	81.5		
	For heavy vehicles [30]	101.8		

3.2.2. Dynamic Parameters

Besides the economic elements listed in Table 3, it is necessary to find out the attenuation law of different performance indexes, such as *SDPQI*, *IRI*, and *SDSRI*, during the life-cycle, to calculate, respectively, the residual value, additional fuel consumption cost, additional wheel consumption cost, additional warranty cost, and additional accident cost. From Equation (9) and the performance index data of the investigation samples, it is found that the impact of the changes of *SDSRI* and *SDPCI* during the life-cycle on the annual average number of accidents per kilometer is less than 3%, which can be basically ignored. Therefore, only performance models of *SDPQI* and *IRI* during the life-cycle were established in this paper. The relationship between the *SDPQI* and *IRI* performance index data of each investigation sample and the cumulative equivalent single axle loads (CESAL) during the life-cycle is shown in Figure 2.

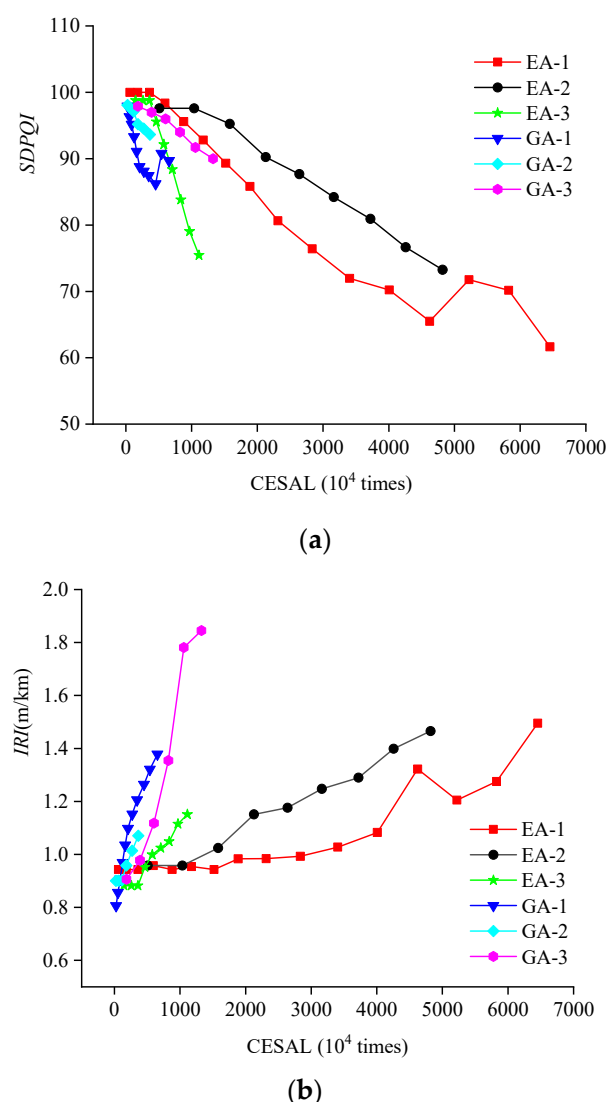


Figure 2. Life-cycle performance index data of the investigation sample: (a) *SDPQI*; (b) *IRI*; CESAL = cumulative equivalent single axle loads; *SDPQI* = performance index of SBDPS; *IRI* = international roughness index.

The conventional methods are difficult to simulate the performance change trend of SBDPS which is complicated, but the principle of the state frequency conversion of the Markov method can better fit the performance change trend of SBDPS [25]. As we all know, construction quality plays an important role in the service performance of a SBDPS, but

construction quality can only gradually reflect differences during the use process, not at the beginning of the use process. Therefore, a life-cycle Markov performance model of *SDPQI* and *IRI* with clear probability characteristics was established, and construction quality was chosen as a random factor to study its impact on the *LCC* of the SBDPS. Construction quality was divided into 15% credibility, 50% credibility, and 85% credibility. Credibility of 15% means that only 15% of cases exceed the level of this case, which indicates that the construction quality is good; 50% credibility indicates that the construction quality is medium; and 85% credibility indicates that the construction quality is poor.

The Markov method is to predict the state probability distribution of the next stage based on the current state or state probability distribution and the state transition probability matrix, which can be calculated with the following Formula (12). In this paper, firstly, an S-type function (for the EA system), an exponential function (for the GA system), and a linear function were used to fit and interpolate *SDPQI* and *IRI* to realize data preprocessing based on the life-cycle performance index data of the investigation samples. Equidistant data was obtained with 1 million times CESAL as the state transition step size. Secondly, the performance index of the SBDPS as divided into 14 state levels with 5 as the step for the EA system (13 state levels for the GA system). Thirdly, the frequency of state transfer was calculated, and the state transition probability matrix was established. The probability cumulative distribution matrix can be calculated based on the distribution probability vector of state, and the expected value of the SBDPS with a credibility of 15%, 50%, and 85% was calculated using the linear interpolation method. The maximum deviation between model output results and verification data is controlled within 5%, which shows the effectiveness of the performance model. The life-cycle performance model of the SBDPS is shown in Figure 3, from where the performance index values of *SDPQI* and *IRI* under different credibility at different stages during the analysis period can be obtained.

$$N_k = P^{k-1} \cdot N_1 \quad (12)$$

where, N_k represents the distribution probability vector of the pavement structure state with the k -th transfer; N_1 represents the initial probability vector; and P represents the state transition probability matrix, in which the elements correspond to the transition probability from one state to the other state.

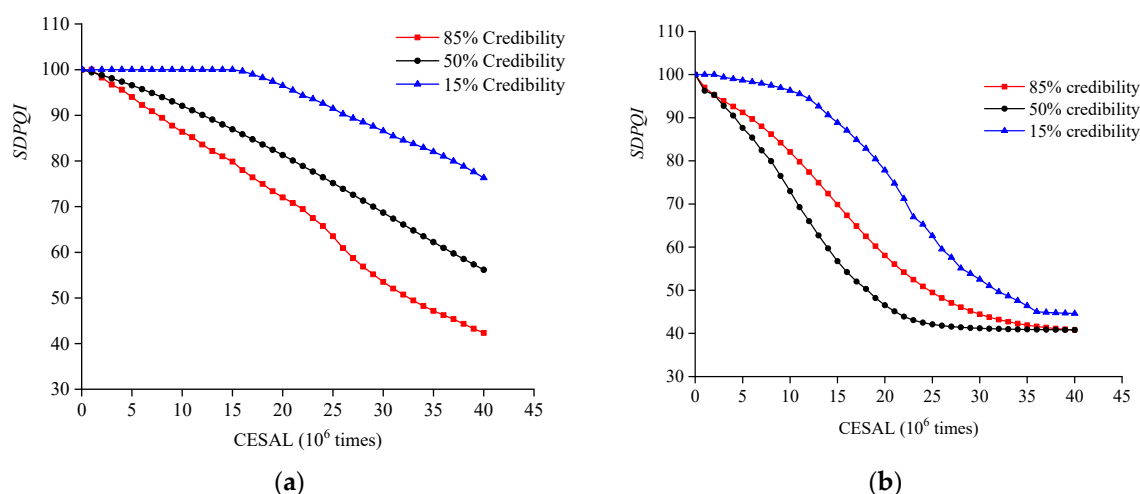


Figure 3. Cont.

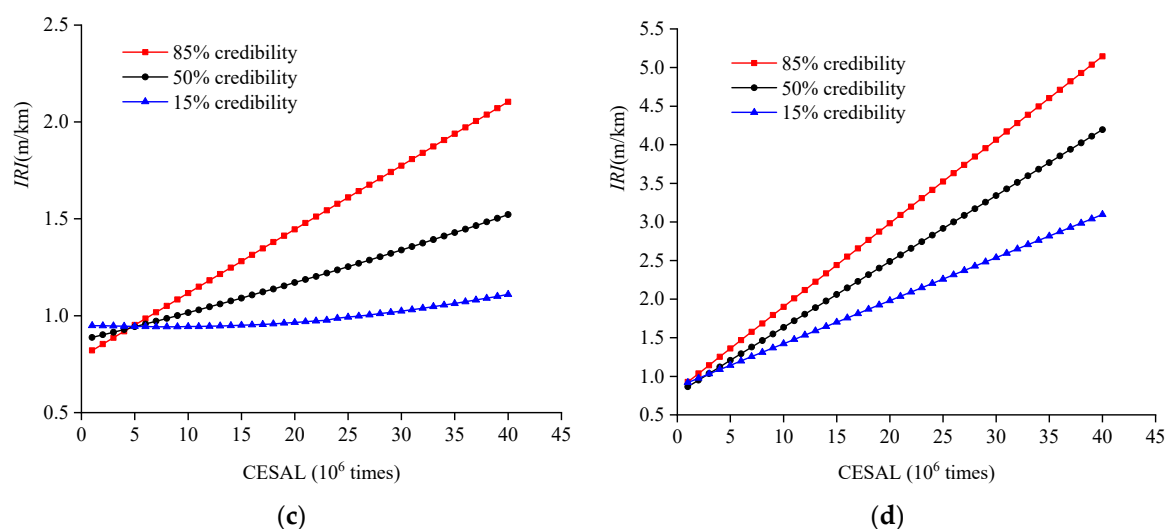


Figure 3. Life-cycle performance model of SBDPS: (a) *SDPQI* of EA system; (b) *SDPQI* of GA system; (c) *IRI* of EA system; (d) *IRI* of GA system; CESAL = cumulative equivalent single axle loads; *SDPQI* = performance index of SBDPS; *IRI* = international roughness index.

3.3. Representative Traffic Conditions of SBDPS

In order to quantify the impact of traffic conditions on the life-cycle economy of SBDPS, five representative traffic conditions for different traffic requirements were designed based on the uniform design method [31]. The uniform design method is a method to find the representativeness in the variation range of independent variables, the core idea of which is to make the test points evenly distributed in the test range and, meanwhile, make the overall characteristics of the system still relatively well-reflected. The characteristics of representative traffic conditions comprise three parameters: initial traffic volume, traffic volume growth, and the class of heavy loads, as shown in Table 3.

Table 3. Characteristics of representative traffic conditions (pcu = passenger car unit).

Representative Traffic Condition	Initial Traffic Volume (10 ⁴ pcu/Day)	Traffic Volume Growth (%/Year)	Class of Heavy Loads		CTV (10 ⁴ pcu) ^{2*}	CESAL (10 ⁴ Times)
			Grade of Loads	Ratio of Big and Heavy Vehicles		
1	2	8	TTC5 ^{1*}	15%	10,575 ^{3*}	273 ^{3*}
2	3	4	TTC2	25%	13,146	622
3	4	10	TTC3	35%	23,268	1569
4	5	6	TTC1	45%	24,055	2935
5	6	2	TTC4	5%	23,980	163

^{1*} TTC represents the distribution coefficient of big and heavy vehicles type [32]. ^{2*} CTV represents the cumulative traffic volume. ^{3*} CTV and CESAL of representative traffic conditions from 1 to 5 refer to the cumulative amount during the analysis period (10 years).

3.4. Reliability Verification of LCC Analysis Model

Since many parameters are derived from estimates and assumptions during the analysis, the life-cycle economy analysis needs to be accompanied by a reliability evaluation, which can be determined by the uncertainty analysis method, mainly to prevent the calculation parameters with biased values from exerting too much influence on the calculation results [33]. The total uncertainty of the LCC analysis model, obtained by the following Formula (13), mainly consists of the uncertainty of the original data and the uncertainty of the algorithm. When the total uncertainty of the calculation results is less than 0.1, the analysis method can be considered reliable. The uncertainty of the calculated parameters in this paper is shown in Table 4.

$$U = \sqrt{U_r^2 + U_a^2} \quad (13)$$

where, U represents the total uncertainty, U_r represents the uncertainty of the original data, and U_a represents the uncertainty of the algorithm.

Table 4. Uncertainty of calculation parameters.

Calculation Parameters	Uncertainty of the Original Data	Uncertainty of the Algorithm
Construction cost	0	0.025
Daily maintenance rate	0.05	0.025
Cost of repairing	0.029	0.025
Work zone	0.1	0.05
Toll	0.01	0.025
Fuel price	0.05	0
Price of wheels	0.075	0
Price of vehicles	0.075	0
Loss for every accident	0.143	0.05
Value of passengers' time	0.143	0.05

The total uncertainty results of the *LCC* of SBDPS is as shown in Table 5, where it can be seen that the total uncertainty of the calculation results of the *LCC* of SBDPS under representative traffic conditions is within 0.1, verifying the reliability of the *LCC* analysis approach used for SBDPS.

Table 5. Total uncertainty of *LCC* of SBDPS under representative traffic conditions.

Representative Traffic Condition	EA System			GA System		
	15% Credibility	50% Credibility	85% Credibility	15% Credibility	50% Credibility	85% Credibility
1	0.051	0.051	0.051	0.057	0.056	0.057
2	0.051	0.050	0.050	0.057	0.055	0.055
3	0.051	0.049	0.049	0.055	0.061	0.065
4	0.048	0.055	0.058	0.057	0.081	0.081
5	0.050	0.050	0.051	0.057	0.056	0.057

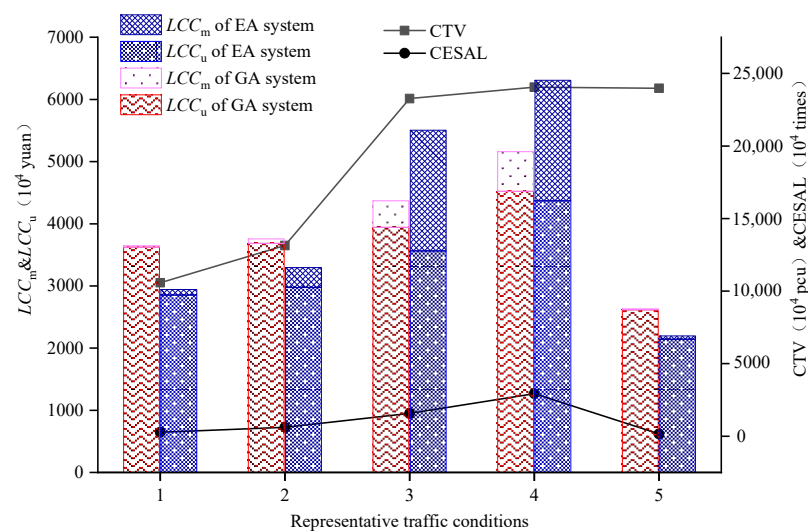
4. *LCC* Analysis of SBDPS

4.1. *LCC* Composition Evaluation of SBDPS

Based on the calculations established above, the *LCC* composition of SBDPS under representative traffic conditions was calculated as shown in Table 6. The manager and user costs of SBDPS under representative traffic conditions are shown in Figure 4 (The manager and user costs of a certain system in Figure 4 represents the average value under all the credibility scenarios). As shown in Figure 4, compared with the cumulative traffic volume, the CESAL has a closer relationship with the *LCC* of SBDPS. With the increase in CESAL, the manager and user costs of the EA system and the GA system increase, and the increase rate of manager and user costs of the GA system is higher than that of the EA system. The reason for the phenomenon is that the GA system is more prone to rutting under higher CESAL, greatly reducing the flatness and structural safety, increasing maintenance requirements, and then, causing traffic congestion, resulting in continuously rising manager costs and user costs.

Table 6. The LCC composition of SBDPS under representative traffic conditions (unit: 10^4 yuan).

Representative Traffic Condition	LCC Composition		EA System			GA System		
			15% Credibility	50% Credibility	85% Credibility	15% Credibility	50% Credibility	85% Credibility
1	LCC_m	$C_c - C_r$	2943.57	3000.55	3042.59	2171.09	2299.28	2321.72
		C_m	602.23	602.23	602.23	588.85	588.85	588.85
		C_{lost}	0	0	0	0	0	0
	LCC_u	C_o	11.55	26.42	35.65	63.69	91.44	109.99
		C_d	0	0	0	0	0	0
2	LCC_m	$C_c - C_r$	2943.57	3092.30	3211.85	2201.67	2420.55	2532.64
		C_m	602.23	602.23	602.23	588.85	588.85	588.85
		C_{lost}	0	0	0	0	0	0
	LCC_u	C_o	19.84	78.08	114.36	224.22	333.53	407.31
		C_d	0	0	0	0	0	0
3	LCC_m	$C_c - C_r$	2951.43	3405.88	3660.46	2462.98	2712.56	2816.72
		C_m	602.23	602.23	602.23	588.85	744.91	913.70
		C_{lost}	0	0	0	0	179.70	271.77
	LCC_u	C_o	111.41	474.58	701.42	1387.03	1893.66	1846.35
		C_d	0	0	0	0	276.17	413.86
4	LCC_m	$C_c - C_r$	3370.53	3677.75	3923.38	2852.73	2769.26	2715.94
		C_m	602.23	713.7	834.27	744.91	1434.10	1461.66
		C_{lost}	0	170.24	272.54	170.24	523.27	440.10
	LCC_u	C_o	123.36	503.3	603.76	1573.02	1049.62	1232.47
		C_d	0	276.17	413.86	0	1031.22	924.98
5	LCC_m	$C_c - C_r$	1980.00	2028.43	2034.84	1452.00	1600.64	1609.95
		C_m	602.23	602.23	602.23	588.85	588.85	588.85
		C_{lost}	0	0	0	0	0	0
	LCC_u	C_o	7.29	16.42	22.03	39.35	56.22	67.88
		C_d	0	0	0	0	0	0

**Figure 4.** The LCC composition of SBDPS under representative traffic conditions: CESAL = cumulative equivalent single axle loads; CTV = cumulative traffic volume; LCC_m = manager cost; LCC_u = user cost; pcu = passenger car unit.

4.2. Weight Analysis of LCC Component

Based on Table 6, the user cost and the sum of the manager and user costs in the EA system and the GA system under representative traffic conditions and credibility are shown in Figure 5. It can be found from Figure 5 that, if the manager cost is only considered, the manager cost of the EA system is lower than the GA system when the CESAL is higher than 28 million times, which indicates the EA system is only applicable to bridges under traffic conditions when the CESAL is higher than 28 million times. The sum of the manager and user costs in the EA system is lower than in the GA system when the CESAL is higher than 11 million times, which indicates that the EA system is applicable to bridges under traffic conditions when the CESAL is higher than 11 million times.

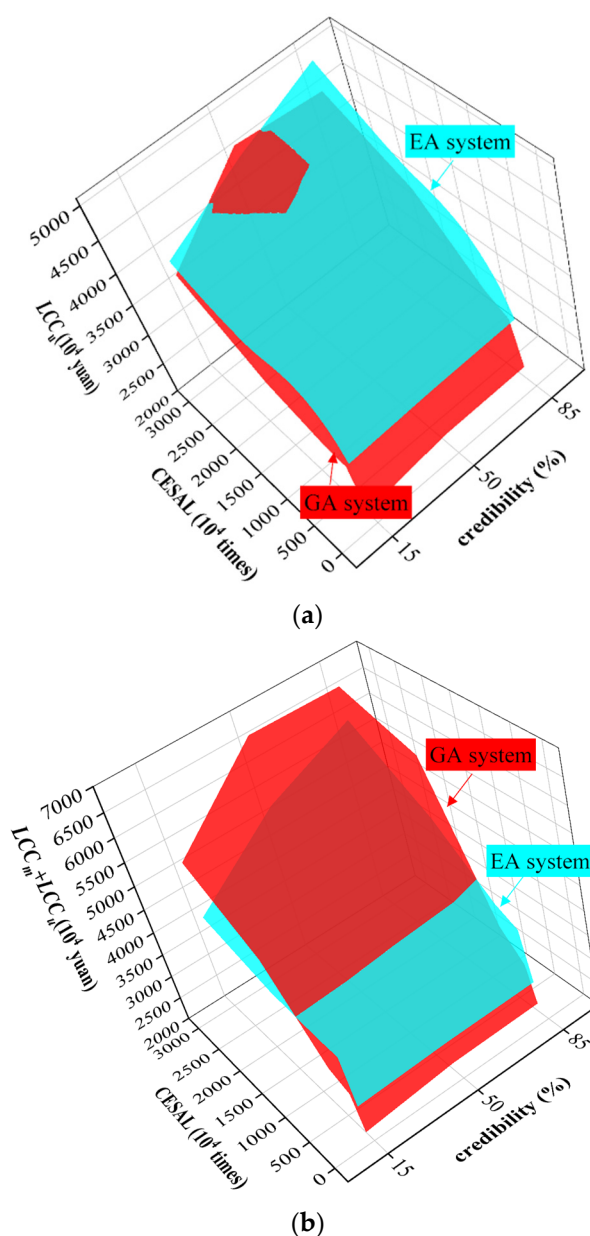


Figure 5. The LCC_m and $(LCC_m + LCC_u)$ of the EA system and the GA system under representative traffic conditions and different credibility: (a) LCC_m ; (b) $LCC_m + LCC_u$; CESAL = cumulative equivalent single axle loads; LCC_m = manager cost; LCC_u = user cost.

Obviously, whether to consider the user cost directly determines the different SBDPS selection for representative traffic conditions. In addition, compared to the user cost, bridge-

management departments who decides the selection of SBDPS may pay more attention to manager costs that are more closely related to themselves. Therefore, the weight of user costs should be analyzed so that the user costs can be considered more reasonably in life-cycle economy analysis of SBDPS. It is currently difficult to study the managers' idealized attention with theoretical methods, so the expert-scoring approach becomes the most direct way to study their minds. Based on the expert-scoring approach, five managers and five scholars were investigated about their concerns regarding user costs, and the results were converted into the conversion factors as listed in Table 7.

Table 7. The conversion factors of user costs.

Sample Number	Manager Cost	Vehicle Operating Cost	Traffic Delay Cost
Scholar 1	1	0.27	0.12
Scholar 2	1	0.30	0.11
Scholar 3	1	0.19	0.69
Scholar 4	1	0.50	1.00
Scholar 5	1	0.50	0.15
Manager 1	1	0.12	0.36
Manager 2	1	0.11	0.37
Manager 3	1	0.14	0.57
Manager 4	1	0.15	0.22
Manager 5	1	0.12	0.19
Average ^{1*}	1	0.24	0.38

^{1*} The average value was calculated by removing the maximum and minimum values.

It can be seen from Table 7 that both scholars and managers think that user costs should be considered in the life-cycle costs analysis of SBDPS, but that they are not as important as the manager costs. Among them, three scholars believe that the importance of vehicle operation costs is higher than that of traffic delay costs. They think that the vehicle operation costs are indirectly related to the structural health of SBDPS, which should be paid attention to. Other scholars and managers believe that the importance of vehicle operation costs is lower than that of time delay costs. Compared with road pavement scheme, the SBDPS is generally higher in flatness, and the amount of vehicle operation costs diluted to each vehicle is small, so it is unnecessary to pay more attention to it. Traffic blocks cause great negative social impact, so they should be paid more attention.

By removing the maximum and minimum values and taking the average value of the ten investigation results above, the LCC calculation of SBDPS was obtained as shown in the following Formula (14). The user cost can be considered more reasonably in the life-cycle economy analysis of SBDPS in Formula (14) because the manager cost that the bridge-management department pays more attention to has higher weight, and the user cost is also appropriately considered to cover the impact of social impact on the bridge-management department. Based on Table 6 and Formula (14), the LCC of the EA system and the GA system under representative traffic conditions and different credibility are shown in Figure 6. It can be seen from Figure 6 that the GA system has better LCC when the CESAL is low, while EA system has better LCC when the CESAL is high. The breaking point of CESAL for the life-cycle economic analysis of the EA system and the GA system is 15 million times, which indicates the applicable traffic conditions of the GA system has been increased from lower than 11 million to lower than 15 million by considering the LCC to replace the sum of manager and user costs.

$$LCC = LCC_m + 0.24C_o + 0.38C_d \quad (14)$$

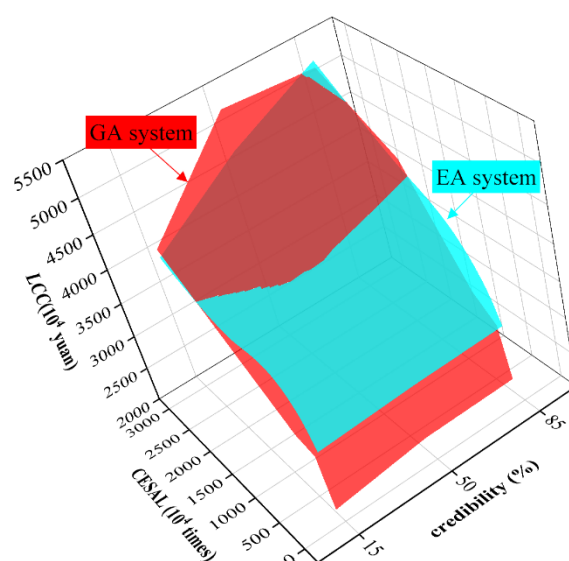


Figure 6. The LCC of the EA system and the GA system under representative traffic conditions and different credibility: CESAL = cumulative equivalent single axle loads; LCC_u = user cost.

4.3. LCC Comparison of Different SBDPS

The LCC of the EA system and the GA system under representative traffic conditions and different credibility are shown in Figure 7. Figure 7 shows that credibility, influenced by random factors such as construction quality, led to the gradual increase in the LCC of the EA system and the GA system under the same CESAL with the increase in CESAL. The reason for this phenomenon is that the higher credibility means the faster performance degradation speed of SBDPS, which causes more maintenance requirements, resulting in more manager costs and user costs. It indicates that the LCC analysis of the SBDPS should consider the influence of random factors such as construction quality. It is worth noting that under the No.4 representative traffic condition, construction quality at 50% credibility and 85% credibility had little effect on the LCC difference of the GA system. This is mainly due to the CESAL being very high. For the GA system with medium construction quality and below that, they are prone to damage, resulting in multiple maintenance requirements, which in turn will cause a large amount of manager costs and user costs, indicating that bridges with high demand for heavy-duty vehicles should be prioritized to consider adopting the EA system.

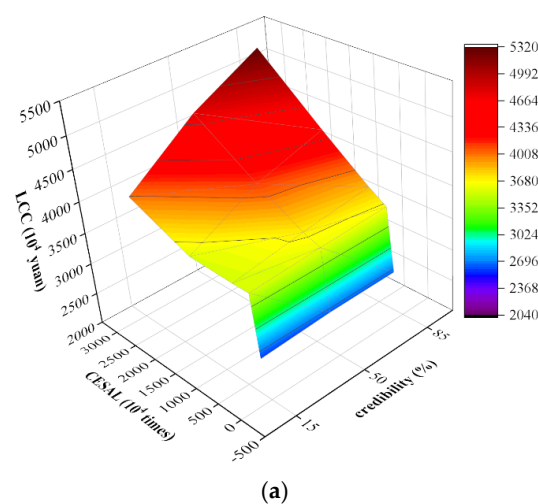


Figure 7. Cont.

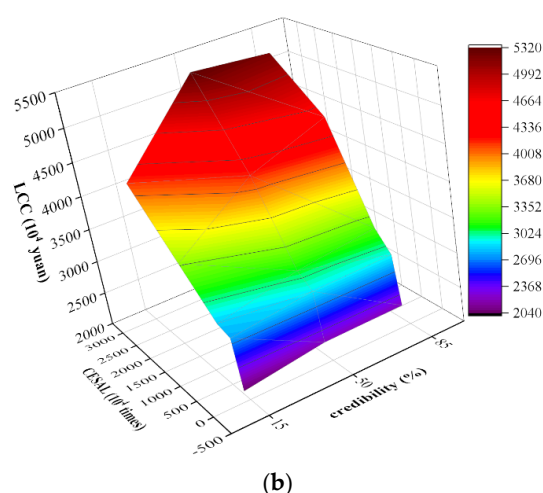


Figure 7. The *LCC* of the EA system and the GA system under representative traffic conditions and different credibility: (a) EA system; (b) GA system; CESAL = cumulative equivalent single axle loads.

5. Conclusions

In this paper, by referring to the existing *LCC* analysis framework for road pavement schemes, a targeted *LCC* checklist based on the structural and management characteristics of the SBDPS was reasonably proposed. Construction quality was first considered in the *LCC* analysis of SBDPS by investigating actual engineering projects and establishing a life-cycle Markov performance model with clear probability characteristics. Therefore, an updated and comprehensive *LCC* analysis approach was proposed to evaluate the economy of the SBDPS. The reliability of the proposed *LCC* analysis approach was verified based on the uncertainty analysis method. Based on the proposed comprehensive *LCC* analysis approach, user costs can be considered more reasonably in the *LCC* analysis, the applicability of the EA system and the GA system under representative traffic conditions and different credibility can be reasonably compared, and the reference value for the breaking point of CESAL for the *LCC* of the EA system and the GA system can be obtained. The detailed conclusions of the study are as follows.

- (1) The total uncertainty of the calculation results of the *LCC* of SBDPS under representative traffic conditions is all within 0.1, indicating the life-cycle economic analysis method of SBDPS is reliable.
- (2) Compared with the cumulative traffic volume, CESAL has a closer relationship with the *LCC* of SBDPS. With the increase of CESAL, the manager cost and user cost of the EA system and the GA system increase, and the increase rate of manager cost and user cost of the GA system is higher than that of the EA system.
- (3) Based on the expert-scoring approach, a weight of user cost was analyzed to ensure more reasonable user cost in the life-cycle economy analysis of SBDPS. The GA system has better *LCC* when the CESAL is lower, while the EA system has better *LCC* when the CESAL is large. The breaking point of CESAL for the life-cycle economy of the EA system and the GA system is 15 million times.
- (4) With the increase in CESAL, credibility, influenced by random factors such as construction quality, leads to a gradual increase in the *LCC* of the EA system and the GA system under the same CESAL, indicating that the life-cycle economic analysis of the SBDPS should consider the influence of random factors such as construction quality.

The comprehensive *LCC* analysis approach in this paper can provide an effective method for bridge-management departments to consider not only the initial construction cost, but also other costs during the whole service process, and also can provide suggestions for bridge-management departments to make a reasonable selection on SBDPS.

6. Limitations of the Study

In this research, an updated and comprehensive LCC analysis approach for SBDPS was proposed to compare the applicability of SBDPS under representative traffic conditions and different credibility (construction quality as a random factor). This study was conducted as initial theoretical research, and the comprehensive LCC analysis approach for SBDPS will be employed into an algorithm or software after further research work to promote its application in actual engineering projects.

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Abbreviations

The full names and corresponding abbreviations used in the manuscript are listed as follows.

SBDPS	Steel bridge deck pavement scheme
LCC	Life-cycle cost
CESAL	Cumulative equivalent single axle loads
SDPQI	Performance index of SBDPS
IRI	International roughness index of SBDPS

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