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Optimization of Preventive Maintenance Timing of Highway Bridges Considering China's "Dual Carbon" Target

Lunyou Pei [1], Bing Wang [2], Ying Liu [1] and Xiaoling Liu [1,*]

[1] Faculty of Maritime and Transportation, Ningbo University, Ningbo 315211, China; peilunyou@163.com (L.P.); liuying2057@163.com (Y.L.)
[2] School of Civil & Environmental Engineering and Geography Science, Ningbo University, Ningbo 315211, China; wangbing050114@163.com
* Correspondence: liuxiaolingseu@163.com

Abstract: The dual carbon target is a two-stage carbon reduction goal proposed by China, while the bridge maintenance strategy does not consider the need for sustainable development. Therefore, this article studies the optimization of bridge maintenance timing under China's dual carbon goals. Firstly, this paper aims to minimize the total cost of maintenance and carbon emissions, considering the continuous effects of carbon pricing and emissions in the context of the dual carbon goals. The CHINAGEM-E model is employed to predict carbon prices, and a preventive maintenance decision-making method for highway bridges is established. Secondly, based on the theory of material residual strength, a degradation model for the technical condition of highway bridges is constructed. Finally, an in-depth case analysis of an in-service highway bridge is conducted to derive optimal maintenance solutions under three scenarios. In comparison to scenarios considering only maintenance costs or those based on benchmark carbon prices, the comprehensive maintenance cost under the dual carbon targets is the highest. In the total maintenance cost, carbon emission costs constitute over 50%, emphasizing the need for increased attention to carbon emission cost studies in future maintenance research. The methodology proposed in this paper is the first to connect carbon prices with the timing of preventive maintenance for bridges, providing a more scientific and sustainable basis for future highway bridge maintenance decisions.

Keywords: highway bridge; preventive maintenance; strategy optimization; dual carbon goals; technical condition degradation; carbon price

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1. Introduction

With the global promotion of the concept of sustainable development, governments, research institutions, enterprises, and various organizations have embarked on an extensive array of research and practical initiatives focused on green and low-carbon strategies [1].

China is also actively implementing a national strategy to address climate change, announcing the goals and vision of carbon peak and carbon neutrality (dual carbon) [2]. According to statistics, the proportion of global road traffic in greenhouse gas emissions is about 15% [3]. As an important part of road traffic, the proportion of energy consumption and emissions of highway bridges cannot be ignored.

By the end of 2022, the number of highway bridges in China has reached 1.0332 million [4]. Following the substantial construction of bridges in 2000, the highway bridge management department confronts a substantial burden of maintenance responsibilities. Under the premise of safety and reliability, preventive maintenance is one of the important strategies of bridge maintenance [5]. The concept of preventive maintenance is to maintain the operation service function of the bridge at the lowest cost by applying the correct measures to the appropriate bridge structure at the suitable time. This method can avoid the large amount of carbon emissions and waste of resources generated by emergency repair and reconstruction and can also improve the sustainability and economy of the bridge [6]. Therefore, research on optimizing the timing of preventive maintenance of highway bridges under the background of dual carbon can not only achieve the goals of dual carbon economy, but also improve the safety and reliability of highway traffic and reduce energy consumption and emissions, which has important practical significance and social value.

In recent years, many scholars have carried out a lot of research on the degradation of bridge structure technology, optimization of maintenance decision making, and low-carbon maintenance. In the aspect of bridge technical condition degradation models, Zhao et al. [7] proposed a Bayesian dynamic model to predict the bridge technical condition and tested the Bayesian factor of the model through practical engineering. The results show that the Bayesian dynamic model is suitable for bridge technical condition degradation prediction. Zhang et al. [8] combined Bayesian dynamic linear model with Markov transition theory, used displacement response to evaluate the state of bridge expansion joints, successfully identified the degradation process of expansion joints, and gave the state transition probability. The empirical results show that the method has high calculation accuracy and efficiency. Mašovic et al. [9] proposed an improved stochastic model, which is a semi-Markov bridge degradation model in which Weibull distribution is used to calculate the residence time under conditional conditions. This model has good applicability in bridge management. Goyal et al. [10] proposed a method based on proportional hazards regression, using the bridge database to identify the most critical factors affecting deterioration, and quantified the impact of degradation factors on bridge condition rating.

In terms of optimizing maintenance decisions, Navarro et al. [11] applied life cycle assessment (LCA) combined with the concepts of life cycle cost analysis and social life cycle analysis to evaluate the impact of maintenance activities related to each scheme on users. The results show that this method can reduce the total cost generated during the analysis period by about 58.5%. Wu et al. [12] constructed a life cycle optimization model using a semi-Markov process, and pointed out that the optimization model is affected by many uncertain factors, such as the fluctuation of the discount rate and the change of traffic volume, which require the use of sensitivity analysis or a probability method to study the cost uncertainty. Yang et al. [13] established a decision-making system based on multiple constraints, such as ideal maintenance objectives and use functions. The maintenance management strategy should not only meet the lowest maintenance cost in the whole life cycle, but also meet multiple objectives and constraints related to the performance of the bridge in the whole life cycle. Shi et al. [14] designed an improved NSGA-II (non-down-sorting genetic algorithm II) with double-layer encoding to solve the multi-objective mixed-integer programming model and conducted multiple sets of data experiments to verify the performance of the improved NSGA-II. Hou et al. [15] used an enhanced particle swarm optimization algorithm to solve multi-objective problems related to maximum probability reliability and minimum production cost and demonstrated the effectiveness of this method through case analysis.

In terms of low-carbon bridge maintenance, the current research mainly focuses on bridge LCA. Collings [16] studied the energy consumption and CO_2 emission range of building materials in the construction of medium-span bridges, considered the carbon emissions of different bridge types and different materials, and estimated the CO_2 emissions during bridge maintenance. Bouhaya et al. [17] evaluated the environmental impact of new bridges based on the LCA method with energy consumption and CO_2 emissions as indicators and divided the bridge life cycle into six stages: material production, transportation, construction, maintenance, demolition, and waste disposal. Thormark [18] showed in their study that the most concentrated carbon emissions were in the operation stage, but the emissions in the construction stage also accounted for a high proportion, about 20% of the total. Additionally, certain scholars have integrated environmental costs associated with carbon emissions into the strategy for sustainable bridge maintenance. Kripka et al. [19] aimed to study short-span bridges by incorporating construction, assembly and material transportation costs, life expectancy, and global warming potential into the decision-making process. Kim et al. [20] analyzed the maintenance database to determine the state changes and required maintenance of existing bridges and used the results to predict the environmental impact and cost of continuous bridge maintenance.

In the process of low-carbon development, numerous scholars have proposed methods to reduce carbon emissions. Bi et al. [21], by constructing a dynamic computable general equilibrium (CGE) model, explored the differences in green growth paths under three scenarios: carbon market, carbon tax, and hybrid policies. The results indicate that in the carbon market scenario, although the short-term carbon emission reduction effect may not be very prominent, it can lead to a dual dividend of long-term emission reduction and an increase in gross domestic product (GDP).Qi et al. [22] employed the EEMD-BP-ELM model to forecast both the high-frequency and low-frequency components of future carbon prices in China, integrating trend components with high- and low-frequency components to derive the price range from 2022 to 2060.

Building upon the analysis above, we note that scholars in the field of sustainable maintenance have considered the influence of carbon emissions, yet the evaluation of carbon prices on the sustainability of maintenance practices remains unexplored. A goal of this study is to reflect this point, in the context of achieving carbon peak and carbon neutrality goals, grasp the law of carbon price changes, and accurately predict its future trends [23]. By applying the accurately predicted carbon price to the preventive maintenance process of bridges, it will not only provide scientific maintenance decision-making schemes for maintenance institutions, but also greatly improve the emission reduction effect.

Therefore, the objective of this paper is to propose an environmentally friendly maintenance decision-making model that takes into account carbon emissions. First, we develop a maintenance decision model that minimizes the cost of carbon emissions and the cost of maintenance and outline the preventive maintenance process. Subsequently, based on the material degradation theory, the continuous effect of carbon emissions, and the trend of carbon pricing, the degradation model of the technical condition of road bridges as well as the carbon emission cost model are proposed. Finally, the changing patterns of carbon price and maintenance cost under different scenarios are analyzed and discussed using actual bridges as examples. The model intends to address the issue of environmental impacts in bridge maintenance, so as to assess the comprehensive cost of bridge maintenance behavior more comprehensively.

2. Method

2.1. Introduction to the Optimization Model for Preventive Maintenance of Bridges

Timing decisions for preventive maintenance of bridges not only need to fulfil the requirements of the maintenance authority but must also comply with the logical constraints between the objectives and the relevant norms. In the context of the dual carbon objective, this study considers the economic and environmental benefits of the bridge preventive maintenance process. The total cost of bridge maintenance (denoted by C) is also used as the optimal objective of the model to determine the best maintenance scheme. The specific maintenance decision model is shown in Equation (1).

In this model, we integrate economic and environmental friendliness, intending to provide more comprehensive guidance for bridge maintenance decision making.

$$\min C_i = MC_i + TC_i \tag{1}$$

where C_i represents the total maintenance cost of i scheme; MC_i represents the maintenance cost of i scheme; and TC_i represents the carbon emission cost of using i scheme.

Figure 1 illustrates a specific model for preventive maintenance decision making. Based on the literature and data studies, it is more economical to perform preventive maintained when the structural condition of the bridge is in Class 2. The preventive maintenance of bridges used in this paper is for Class 2 and Class 3 bridges. When the technical condition of the bridge drops below λ, it is the earliest time for preventive maintenance, and the maintenance effect will be enhanced by φ; when the technical condition of the bridge drops to 60 points, it is the latest time for preventive maintenance. The specific preventive maintenance timing λ is then calculated by the model.

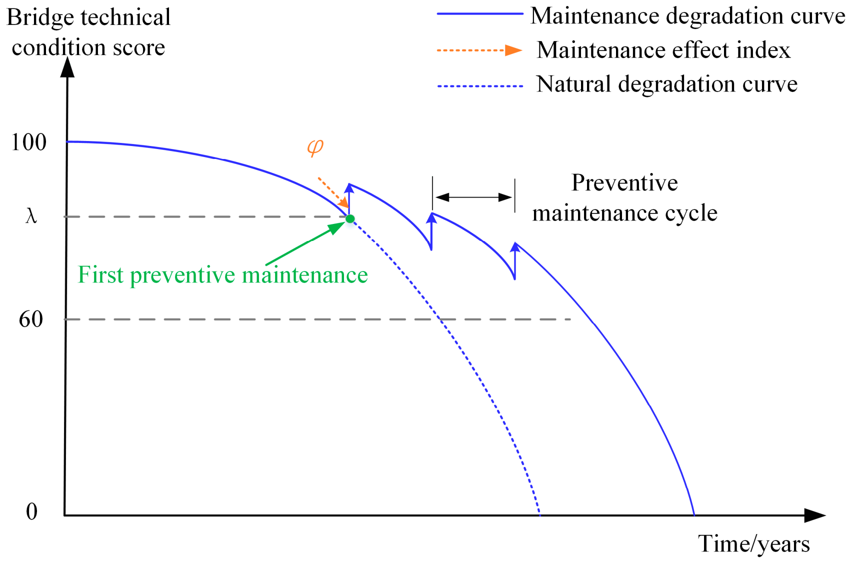

Figure 1. Conceptual model of preventive maintenance decision.

2.1.1. Fundamental Assumptions and Constraint Conditions

After bridge maintenance activities, the structural technical conditions undergo intricate changes. The current research struggles to precisely depict the trend of health status in various structures post different maintenance measures. Hence, simplifying the optimization model for bridge preventive maintenance becomes essential. The following assumptions underpin the preventive maintenance decision optimization model:

- Without considering the specific maintenance measures in the model, the degradation law of bridge technical condition does not change after maintenance.
- After each preventive maintenance, the improvement value of the technical condition of the bridge is the same, set to 8.
- The value of the technical condition index after each maintenance will not exceed the technical condition score after the last maintenance.

When optimizing the maintenance strategy of highway bridges, it is necessary to ensure that the calculation time is not greater than the established maintenance cycle. Therefore, there are the following three constraints:

- When $D(t) \geq \lambda$, perform only routine maintenance;
- When $60 \leq D(t) < \lambda$, take preventive maintenance measures;
- When $t_{p1} + (i-1)\, t_p > T$, the calculation ends.

Where $D(t)$ is the technical condition of the bridge structure, and t is the established maintenance cycle (year) of the bridge structure.

2.1.2. Preventive Maintenance Process for Bridges

Through a comprehensive inspection of the actual situation of the bridge, combined with the evaluation criteria of the technical status of the bridge, the bearing capacity, structural integrity, service life, and overall safety status of the bridge are evaluated. Based on the long-term inspection data of the bridge, a technical condition degradation model is established, and all preventive maintenance schemes are obtained in combination with the preventive maintenance strategy of this paper. The research process is shown in Figure 2.

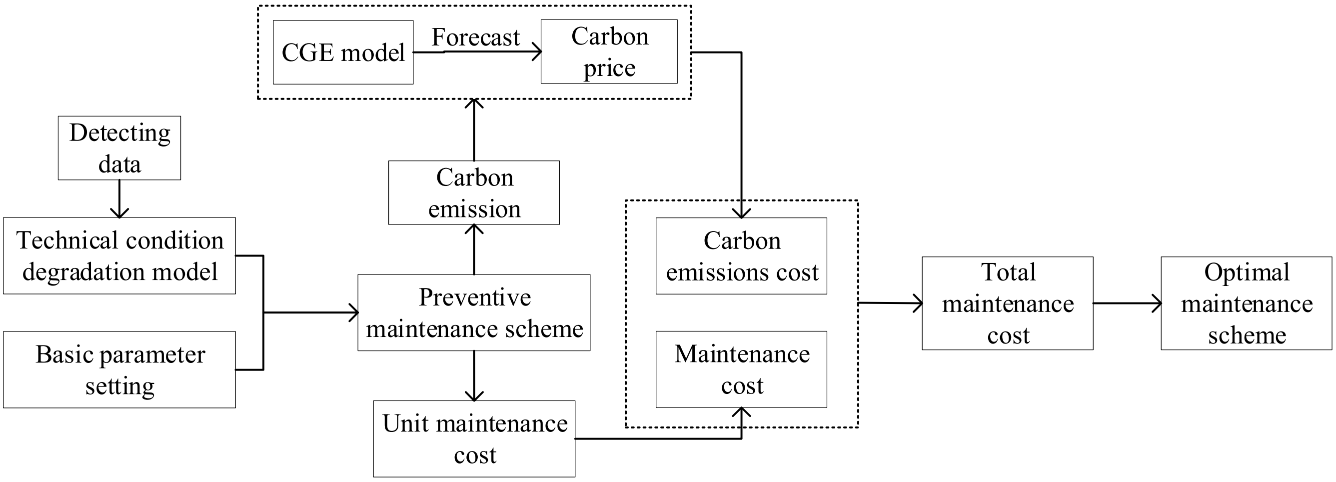

Figure 2. Bridge preventive maintenance flow chart.

2.2. Degradation Law of Bridge Technical Condition

2.2.1. Assessment of Bridge Technical Condition

At present, the technical condition evaluation of highway bridges in China adopts the method of combining hierarchical comprehensive evaluation with a single control index of bridges. Referring to the standard of the Technical Condition Assessment Standard for *Highway Bridges* (*JTG/T H21-2011* [24]), the classification of bridge technical condition is shown in Table 1. Among the classifications, a score of 100 points indicates that the bridge's technical condition is intact, and a score of 0 indicates that the bridge's technical condition is the worst. The scope of preventive maintenance of bridges used in this paper is Level 2 and Level 3 bridges.

Table 1. Classification boundary of bridge technical conditions.

Technical Condition Evaluation	**Technical Condition Grade**				
	Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Description of bridge state	New state	Minor defect	Medium defect	Larger defect	Severe defect
(D)	[90, 100]	[80, 90)	[60, 80)	[40, 60)	[0, 40)

2.2.2. Model of Bridge Technical Degradation

In the decision-making model for the preventive maintenance of highway bridges, understanding the functional relationship between the technical status and time of highway bridges is crucial. The aim is to keep the bridge in a high-performance state through preventive maintenance, optimizing both maintenance funds and strategies. This section, therefore, establishes the degradation function model for highway bridges.

For the same bridge type, the function curves of the degradation model are different due to different regions and load levels. Various studies have established degradation models based on bridge reliability [25–27] and bridge technical condition indicators [28]. For example, regarding the linear degradation model, the method is relatively simple but cannot consider complex and changeable factors, while the exponential function model can consider more factors affecting the degradation of the bridge, but with a lack of theoretical basis. In this paper, the residual strength theory of materials is used for reference. The theoretical formula delineates the degradation trend of material strength, manifesting an initial slow decline followed by a rapid decline, consistent with the degradation pattern observed in a substantial number of bridges in the United States. Based on the material residual strength model in reference [29], this paper establishes the degradation model of highway bridge technical condition as follows:

$$D(t) = 100\left[1 - (t/N)^{b}\right] \tag{2}$$

where t is the service time, N is the target life, and b is the environmental load index.

2.3. Bridge Preventive Maintenance Costs

In the maintenance decision-making process of highway bridges, the remaining life of highway bridges is first predicted, and then the preventive maintenance timing is reasonably arranged according to the development trend of technical conditions during the operation period. During the operation of highway bridges, the time value of funds is considered through the treatment of preventive maintenance. Therefore, the calculation model of the preventive maintenance cost in the planned bridge maintenance cycle is calculated according to Equation (3):

$$MC(t_{p1}, t_p) = \sum_{i=1}^{n(t_{p1},t_p)} MC_i(t_{p1}, t_p)\frac{1}{(1+r)^{t_{p1}+(i-1)t_p}} \tag{3}$$

where $MC(t_{p1}, t_p)$ is the cost of the preventive maintenance of bridges.

Different maintenance measures will bring different maintenance costs. With reference to the maintenance costs in actual case projects, this paper takes the value of CNY 130,000 [30–32]. t_p is the time interval of preventive maintenance; t_{p1} is the start time of the first preventive maintenance; $MC_i(t_{p1}, t_p)$ is the single maintenance cost; $n(t_{p1}, t_p)$ is the number of preventive maintenances carried out during the life cycle of the bridge; i is an integer variable; and r is the discount rate, taking 6% as the reference value [33].

2.4. Carbon Emission Costs

Within the decision-making process for the preventive maintenance of bridges, factoring in the cost of carbon emissions is a pivotal consideration. This encapsulates the influence of maintenance activities on the environment through carbon emissions. To translate carbon emissions into a monetary value, one can use the price of emission allowances in the carbon market as a benchmark. The emission allowance price designates the cost of trading carbon dioxide emission rights in the carbon market, customarily expressed as the price per metric ton of carbon dioxide emission rights. Hence, converting the carbon emissions generated from the preventive maintenance of bridges into monetary terms can be achieved by multiplying them with the price per metric ton of carbon dioxide emission rights, as depicted in Equation (4).

$$TC(t_{p1}, t_p) = \sum_{i=1}^{n(t_{p1},t_p)} T_{(CO_2)i}(t_{p1}, t_p) * C_{(CO_2)i}(t_{p1}, t_p) \tag{4}$$

where $T_{(CO_2)i}(t_{p1}, t_p)$ is the carbon emissions at the time of the i_{th} maintenance. $C_{(CO_2)i}(t_{p1}, t_p)$ is the carbon price at the time of the i_{th} maintenance.

2.4.1. Calculation of Carbon Emissions

The carbon emissions in the bridge maintenance stage are calculated according to the engineering design and completion data [34]. The carbon emissions in the maintenance process are evaluated according to the combination of maintenance plan, project scale, and maintenance materials. Under the preventive maintenance mode, the carbon dioxide emissions of single maintenance are shown in Table 2.

Table 2. Carbon emissions for preventive maintenance method.

Maintenance Segment	**Maintenance Material**	**Waste**	**Construction Machinery Office Space**	**Traffic Impact**	**Total Emissions**
Single-curing carbon emissions/t	300	15	39	101.98	455.98

Using the traditional carbon emission calculation method, the total amount of carbon emissions generated by the bridge during maintenance can be expressed as Equation (5).

$$T_{CO_2} = \sum_{m} F_m \times E_m \tag{5}$$

where T_{CO_2} represents the carbon emissions of the statistical object; F_m represents the carbon emission factor of the m_{th} curing method; and E_m represents the consumption of the m_{th} maintenance method.

Conventional statistical approaches conventionally assume a fixed value for E_{mt} over a specific timeframe. In practice, it is vital to evaluate the influence of delayed emissions [35,36]. Employing the dynamic carbon emission factor serves to capture the delayed effects of carbon emissions being released. The carbon emissions over the time interval [0, T] are expressed by Equation (6).

$$T_{CO_2}(T) = \sum_{m} \sum_{t}^{T} F_{mt} \times E_{mt} \tag{6}$$

where F_{mt} is the dynamic carbon emission factor of the maintenance activity m at time t, and E_{mt} is the carbon emission of the maintenance mode m at time t.

Owing to natural decomposition and degradation mechanisms, the concentration of carbon emissions in the atmosphere typically undergoes an annual decline, consequently diminishing the greenhouse effect. Hence, the dynamic carbon emission factor offers a more accurate approach to characterizing carbon emissions. It takes into consideration potential future variations, not just current concentrations. This is of paramount importance in crafting climate change policies and assessing the influence of carbon emissions. In accordance with the research outcomes presented in reference [37], the computational formula for the dynamic carbon emission factor (Equation (7)) is obtained through the fitting of equivalent carbon emission factors at various time intervals.

$$F_{mt} = -3.43 \times 10^{-5} t^2 - 6.20 \times 10^{-3} t^2 + 9.87 \times 10^{-1} \tag{7}$$

2.4.2. Calculation of Carbon Trading Price

The carbon price is intricately connected to a complex array of external factors, encompassing the economy, energy landscape, climate dynamics, and energy policies. It exhibits distinctive traits, including non-linearity, fluctuation, and multi-frequency attributes [38]. Relying solely on historical data for predicting carbon prices would neglect the impact of future macroeconomic shifts, energy price fluctuations, and relevant policies on carbon pricing. Particularly in the context of China, the dual carbon goals will inevitably drive an increase in carbon pricing. Ignoring this fact would lead to a significant underestimation of China's future carbon prices [22].

CHINAGEM-E stands out as a dynamic recursive computable general equilibrium model of the Chinese economy, accounting for both energy and carbon emissions considerations [39]. Rooted in the foundational CHINAGEM model, this model encompasses input–output structures, production theories, final demand mechanisms, labor and capital dynamics, as well as various miscellaneous equations [40]. Through the utilization of the CHINAGEM-E model, we have the capability to simulate equilibrium trends in carbon pricing across varying scenarios. This paper delineates two scenarios: (1) the baseline scenario and (2) the 2060 carbon neutrality scenario. The baseline scenario provides an illustration of China's future economic development without the dual carbon goals. The 2060 carbon neutrality scenario paints a picture of China achieving the dual carbon goals as per the plan. Before 2023, carbon prices are derived from the actual carbon trading prices in various markets in China and then aggregated using a weighted average algorithm to arrive at the annual composite prices. Within the baseline scenario, carbon prices from 2023 to 2040 are established in accordance with the findings of the International Energy Agency's "World Energy Outlook," while projections for carbon prices from 2041 to 2060 are extrapolated based on historical carbon trading prices. Within the 2060 carbon neutrality scenario, carbon prices are projected based on assumptions within the model.

Drawing from the findings in references [41,42], and utilizing the CHINAGEM-E model based on the predicted future carbon emissions trajectory in both the baseline scenario and the 2060 carbon neutrality scenario, we obtain the forecasted Chinese carbon prices, as depicted in Figure 3. This paper scrutinizes the trajectory of future carbon prices in China. The forecast indicates an ascending trend from 2022 to 2060 under both the baseline scenario and the 2060 carbon neutrality scenario. Significantly, in the 2060 carbon neutrality scenario, carbon prices are projected to ultimately surge to almost five times that of the baseline scenario. It is imperative to bear in mind that the carbon prices forecasted by the CHINAGEM-E model encompass the exertion level needed to realize the dual carbon goals, representing the overall societal carbon cost. While this can serve as a gauge for carbon pricing in the carbon market, it may not be synonymous.

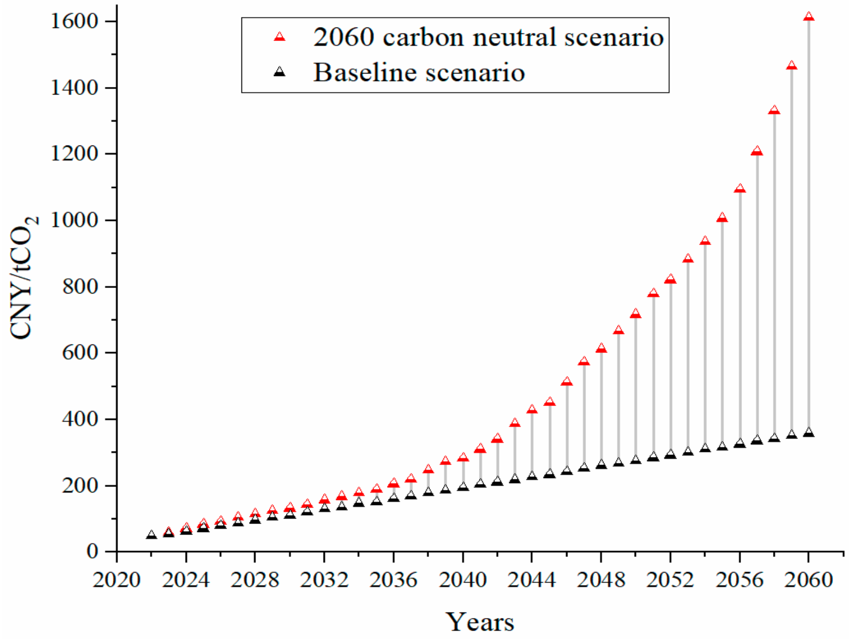

Figure 3. CHINAGEM-E forecasted carbon prices for 2022–2060.

3. Results and Discussion

To validate the proposed maintenance optimization algorithm, we selected a reinforced concrete continuous beam bridge in Ningbo, China, situated on the Yongtaiwen Expressway. The bridge, measuring 382.7 m in total length and featuring two one-way lanes, was constructed and opened for traffic in 1999. As depicted in Figure 4, the overall condition of the bridge is satisfactory, but some components exhibit signs of deterioration.

In 2016, the annual inspection was carried out. According to the results of on-site inspection, the overall condition of the bridge is good, and it is classified as a Class 2 bridge. The main defect of the superstructure is a small number of longitudinal and transverse cracks at the bottom of the beam. The main defects of the substructure are the slight settlement and damage of the abutment slope protection. The main defects of the bridge deck system are several potholes found in the bridge deck pavement, slight damage in the anchorage zone of the expansion joint, multiple concrete rust expansions and exposed reinforcement in the anti-collision guardrail, and about 30% of the drainage holes being blocked. The technical condition of the bridge is evaluated according to the reference [24] and the bridge's technical condition score is 84.8.

Figure 4. Image of bridge's current state.

Owing to the shared environmental context, a specific bridge can function as a representative case for the maintenance environment of bridges in that particular region. This assumption is predicated on the notion that factors impacting maintenance needs, such as climate, traffic patterns, and material properties, display a certain level of uniformity among bridges within the same geographic area. At the same time, these bridges belong to the category of concrete girder bridges. Based on the previous test data of the bridge and 46 similar bridges around it, the fitted curve shown in Figure 5 and the fitting equation of the technical condition of the bridge in its natural state (Equation (8)) are obtained.

$$D(t) = 100\left[1 - (t/45)^2\right] \tag{8}$$

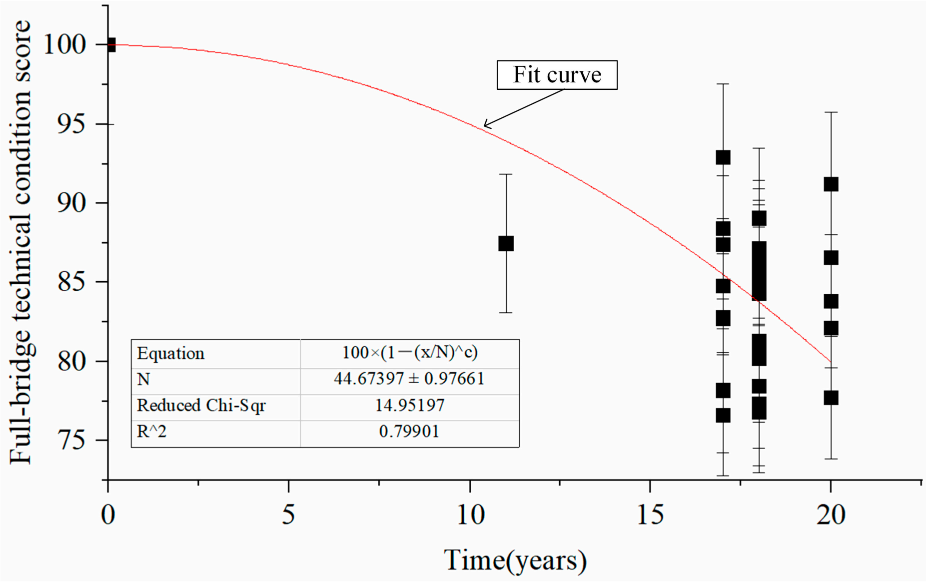

Figure 5. Bridge technical condition fitting curve.

3.1. Bridge Preventive Maintenance Scheme

As shown in Figure 5, using the previous inspection data of the case bridge and the decision-making model (technical condition degradation model and preventive maintenance model) established in this study, all optional preventive maintenance schemes are obtained, including detailed information on the first maintenance timing and the maintenance interval of the maintenance scheme.

In all preventive maintenance schemes, three core scenarios are provided for bridge preventive maintenance. By comparing and analyzing the optimal maintenance strategies of bridges in three scenarios, it provides a decision-making reference for low-carbon maintenance.

3.1.1. Maintenance Cost Based on Time Effect

Under the condition of the same first maintenance timing, the greater the maintenance interval, the smaller the maintenance cost; under the condition of the same maintenance interval, the smaller the first maintenance time, the smaller the maintenance cost. These two trends show that when the maintenance cost is determined, the lower the number of maintenances, the smaller the maintenance cost.

In the case of only considering the maintenance cost, the optimal maintenance plan is that the first preventive maintenance timing is 75 points, the maintenance interval is 5a, and the total maintenance cost is CNY 11.02 million. The bridge degradation curve of the optimal maintenance scheme is shown in Figure 6.

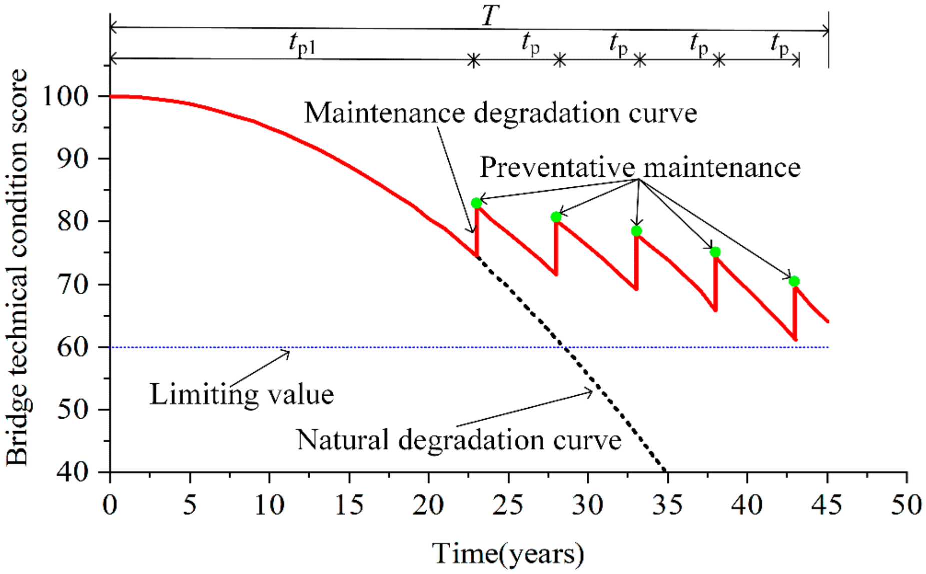

Figure 6. Optimal maintenance scheme in scenario 1.

3.1.2. Comprehensive Maintenance Cost Based on Baseline Carbon Price

In the baseline scenario, the carbon price shows a slow upward trend. In this scenario, the maintenance cost gradually decreases with the increase of maintenance interval. The optimal maintenance scheme is that the first preventive maintenance timing is 90 points, the maintenance interval is 11 years, and the comprehensive maintenance cost is CNY 40.50 million. The bridge degradation curve of the optimal maintenance scheme is shown in Figure 7.

3.1.3. Comprehensive Maintenance Cost Based on the Dual Carbon Goals

In the context of the dual carbon goals, the carbon price gradually exceeds the baseline scenario after 2030, and the carbon price by 2060 is close to five times the baseline carbon price. Under the same maintenance interval, the greater the first maintenance timing, the lower the maintenance cost, and the trend is completely opposite to that of scenario 1. The main reason is that the increasing carbon price leads to a cost of carbon emissions far greater than the maintenance cost. Based on the situation of the dual carbon goals, the optimal maintenance scheme is that the first preventive maintenance timing is 90 points, the maintenance interval is 11 years, the comprehensive maintenance cost is CNY 90.74 million, and the comprehensive maintenance cost increases by CNY 50.24 million. The bridge degradation curve is shown in Figure 7, and the optimal maintenance scheme is the same as that in the baseline scenario.

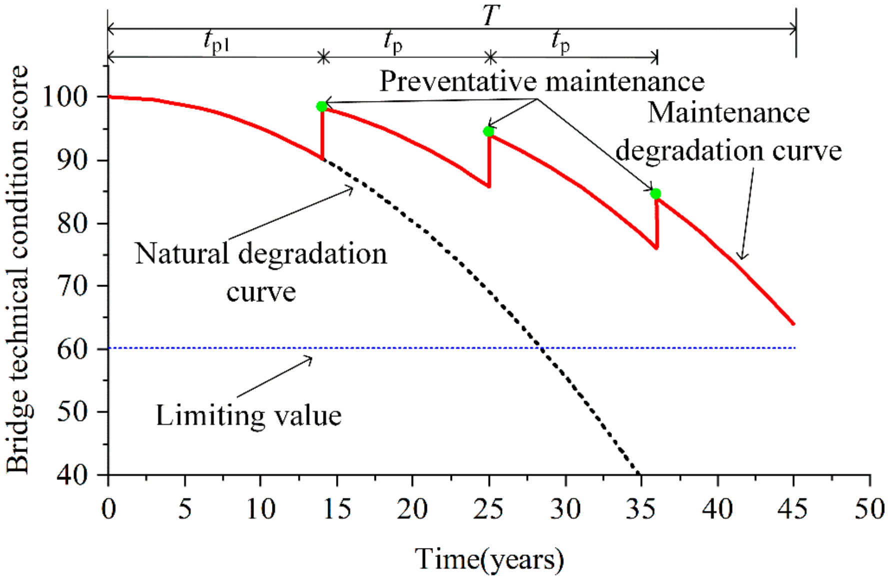

Figure 7. Optimal maintenance scheme in scenario 2.

3.2. Comparative Analysis of the Optimal Solution

As shown in Figure 8, the maintenance cost is the highest in scenario 3 and the lowest in scenario 1. As shown in Figure 9, of the two scenarios considering the cost of carbon emissions, the cost of carbon emissions in scenario 3 is the highest. In scenario 3, the carbon price under the dual carbon goals is considered. Due to the rapid rise of the carbon price, the cost of carbon emission is gradually increasing, and the comprehensive cost of bridge maintenance is also increasing.

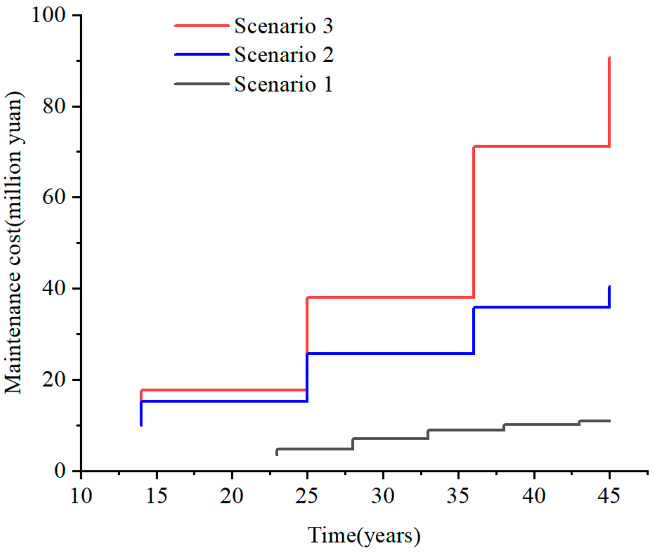

Figure 8. Maintenance cost of optimal maintenance scheme.

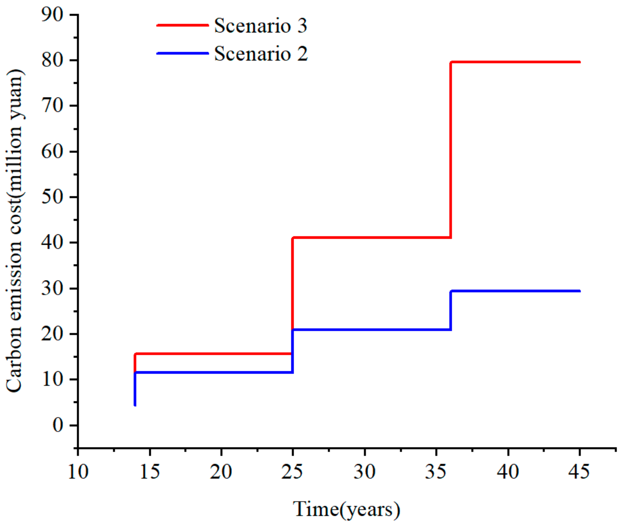

Figure 9. Carbon emission cost of optimal maintenance scheme.

3.3. Discussion

With China's goal of achieving carbon peak and carbon neutrality, the "double control" action, that is, controlling total energy consumption and improving energy efficiency, has become an important driving force, requiring all industries to significantly reduce carbon emissions [43]. In this context, policymakers believe that the implementation of carbon pricing is one of the effective means to encourage the construction industry to eliminate high-carbon development [44]. In addition, in the process of promoting carbon neutrality in China, implementing zero-carbon standards and establishing a carbon emissions trading market will be the main measures to regulate and constrain the construction industry. These changes will also have a profound impact on the maintenance of bridges and other infrastructure. Therefore, it is a crucial task to evaluate the emission reduction effect and sustainability of existing infrastructure.

In this study, we incorporate the persistence effect of carbon emissions and carbon price forecasts into the framework of bridge preventive maintenance decision making and analyze the differences in maintenance decisions under different maintenance scenarios through a case study. The persistent effect of carbon emissions is the level of destruction of greenhouse gases, including carbon dioxide, at a certain time in the future. Due to natural decomposition and destruction mechanisms, the concentration of carbon emissions in the atmosphere usually decreases every year, which also weakens the greenhouse effect [45].

As shown in Figure 10, in the two scenarios considering carbon prices, the average cost of carbon emissions accounts for more than 50% of the total costs, which is much higher than the maintenance cost. At the same time, the average cost of carbon emissions in scenario 3 is higher than that in scenario 2. The research in this paper can provide guidance for conservation agencies and researchers in making actual conservation decisions and achieve the goal of low-carbon conservation while also achieving lower-cost conservation. Of course, the research in this paper is limited by the lack of data samples, and only highway girder bridges within the same area are considered. In future research, more bridge data should be added to optimize the maintenance decision-making framework of this paper.

The goal of curbing carbon emissions through carbon trading will also lead to the increase of carbon prices. How to achieve a balance between carbon emissions and carbon prices is an important research direction in the future, which is of great significance for bridge maintenance and other infrastructure.

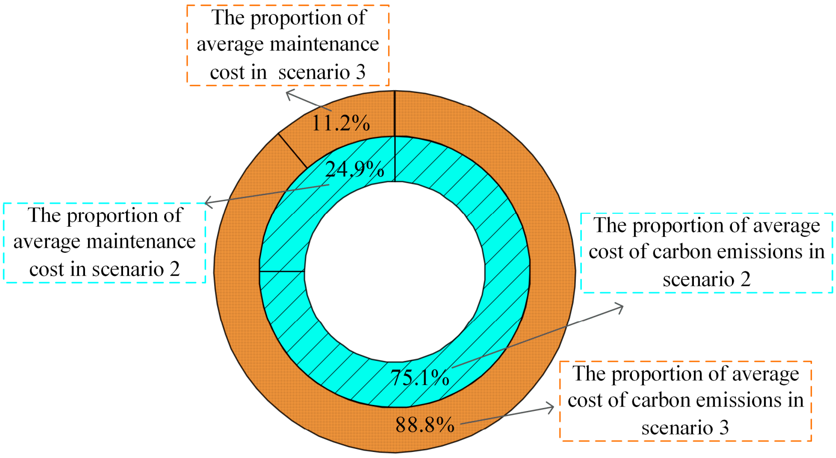

Figure 10. The average cost of carbon emissions of all preventive maintenance programs accounted for by proportion.

4. Conclusions

(1) This paper establishes a decision-making model for the preventive maintenance of bridges with the objective of minimizing the total cost of maintenance and carbon emissions. The model comprises two components: the degradation of a bridge's technical condition and the carbon emission costs. For the first time in this study, carbon pricing is integrated with the timing of preventive maintenance. By examining the impact of carbon price trends under dual carbon goals on the maintenance cost of bridges, optimal maintenance solutions can be provided to maintenance institutions, achieving both economic and sustainable maintenance.

(2) Utilizing the theory of material degradation and data from 46 bridges in the same region, a power-function-based degradation model for the technical condition of highway bridges is established. This model characterizes the natural degradation process of bridges, displaying a trend of slow degradation followed by rapid deterioration.

(3) Through practical calculations, considering the dual carbon targets and the continued impact of carbon emissions, carbon emission costs account for over 50% of the total costs. This case illustrates that future research needs to enhance the focus on carbon emission cost studies in the maintenance process.

(4) In this study, the preventive maintenance decision-making model is only applied to a single bridge. In the future, the model can be extended to the maintenance process of bridge networks at the road network level.

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