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Timing of Preventive Highway Maintenance: A Study from the Whole Life Cycle Perspective

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Abstract: As the mileage of China's highways increases, the focus of highway development has shifted from construction to maintenance and management. With the rapid increase in highway traffic, the overuse of highways, combined with the effects of climate change, has accelerated the occurrence of highway problems and poses new challenges to maintenance strategies. From a system optimization perspective, this paper examines the problem of determining the optimal timing of preventive maintenance on highways. To overcome the shortcomings of this method, which cannot reflect the economic benefits and costs, the total benefits and costs were calculated for different pavement ages within a given analysis period, based on the framework of life cycle analysis. The maintenance timing program with the highest cost-benefit ratio was taken as the optimum maintenance timing program and an example analysis was adopted to validate the feasibility of this method. When the timing of preventive maintenance is later in a pavement's life cycle, the total life cycle benefit decreases while the total life cycle cost increases. Compared to previous studies, this paper considers both direct and indirect influences simultaneously, showing that indirect influence contributes to shortening the timing of pavement preventive maintenance.

Keywords: whole life cycle; preventive highway maintenance; benefits and costs ratio

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Academic Editors: Yang (Jack) Lu, Yong Zheng, Ronghua Xu and Bin Li

Received: 12 November 2024
Revised: 18 January 2025
Accepted: 23 January 2025
Published: 26 January 2025

Citation: Wubuli, A.; Li, F.; Cao, S.; Zhang, L. Timing of Preventive Highway Maintenance: A Study from the Whole Life Cycle Perspective. *Sustainability* **2025**, *17*, 1009. https://doi.org/10.3390/su17031009

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1. Introduction

China's vast land area, diverse geological and meteorological conditions, and challenging environments create a unique context for highway infrastructure. Under the combined influence of complex surface components and hydrogeological factors—such as unfavorable climate conditions and high traffic density—China's highways experience a variety of structural and functional issues. Even the same type of highway issue can have differing causes, stages of development, and varying degrees of severity. To ensure the quality and reliability of highway transportation, it is essential to establish a maintenance management system tailored to the scale, geographical diversity, and climatic characteristics of the country's highway network. This system could emphasize the importance of enhancing the technical and scientific aspects of maintenance, reducing costs, and improving efficiency to meet the demands of sustainable highway management.

From a whole life cycle perspective of highway management—encompassing design, construction, and operation—the importance of preventive maintenance lies in its ability to prevent issues from escalating to a level that compromises road functionality while keeping construction costs under control. Preventive highway maintenance offers numerous

advantages, including a strong theoretical foundation, advanced technologies, scientifically informed decision-making, standardized procedures, and economic benefits.

This type of maintenance is primarily applied to the repair of road surface layers, particularly during the early stages of highway issues before they fully develop. By addressing potential problems proactively, preventive maintenance helps preserve the continuously high performance of highways. To maximize its economic benefits, it is necessary to evaluate the rationality and applicability of maintenance measures and to focus on the optimal timing of their implementation. Properly scheduling preventive maintenance is key to achieving the best economic outcomes while ensuring the long-term sustainability of highway infrastructure.

To address the challenges posed by the heavy workload and strict timing requirements of the highway maintenance and management associated with China's extensive road network, this article reviews the relevant literature and analyzes the various factors influencing highway operational costs. A user-oriented cost-benefit model is also developed to determine the optimal timing for implementing preventive maintenance by comparing the costs and benefits throughout the highway's life cycle.

This study focuses on the practical issues faced by highway management departments, aiming to provide a tool for cost-benefit analysis and identify the optimal timing decisions for preventive maintenance. The goal is to enhance the scientific and economic management of highways, ensuring sustainability and efficiency in maintaining the road network. This article also considers both user and management costs but focuses on the maintenance of common highways, without addressing the complexities of composite structures such as national-level highways and provincial roads.

The structure of the paper is organized as follows. Section 2 provides a systematic summary and review of domestic and international research findings related to highway maintenance. Based on this review, the research objectives and significance of this study are clarified. Section 3 focuses on a quantitative calculation of the benefits derived from user cost savings and environmental cost savings following pavement preservation. It constructs an econometric model that establishes the relationship between vehicle travel time cost savings, vehicle travel cost savings, vehicle safety cost savings, and tailpipe emission cost savings, with relevant indicators such as pavement condition and traffic volume. Section 4 explores the optimal timing for preventive pavement maintenance within the framework of whole life cycle analysis. It evaluates various timing options based on their cost-benefit ratios to identify the program timing that yields the highest cost-benefit ratio. Section 5 offers our conclusions.

2. Literature Review

Due to limited maintenance budgets and aging highway infrastructure networks, the challenge for road managers is to make the most cost-effective decisions regarding highway maintenance to better maintain pavement service quality and ensure driving safety for road users [1].

The most utilized maintenance decision-making method is the decision tree method, which requires determining a comprehensive index to be used for asphalt pavement performance evaluation, then determining the weights of any influencing factors [2]. The decision tree method is concise and easy to understand, with strong application and operability, but the selection of decision tree thresholds and weights mainly depends on the experience of the local engineers, which is subjectively influenced.

The mathematical planning method is also widely used in pavement management. This is based on mathematical theory and sets optimization objectives and functions, solving pavement maintenance as an optimization problem [3–5]. Mathematical planning

optimization methods based on mathematical principles have a certain degree of scientific applicability, but in practical applications there is not necessarily a single optimal solution, and for large-scale road network planning problems, the solving speed is slow.

With the rise of artificial intelligence research, new uses for artificial intelligence models in pavement management decision-making are also emerging [6–11]. The advantage of the artificial intelligence algorithm decision model is that the computer's powerful arithmetic power can optimally solve a large number of maintenance combinations in a short period of time, but the disadvantage is that it requires long-term high-quality data from the pavement management system, which is a demanding requirement for the algorithm designer's computer theory and road maintenance management level.

The existing methods have the following shortcomings: the determination of the maintenance timing is mainly based on the physical state of the pavement, the degree of damage, the quality of traffic, etc., as the main factors for the determination of the optimal time when the indicators are reduced to a reasonable level. Highway top maintenance is considered to be mainly economic; a method based on the pavement's technical indicators does not adequately take into account the distribution and change of traffic flow caused by the condition of the pavement, and the maintenance time of the highway is not sufficient. The distribution of and change in traffic flow caused by the condition of the road surface, in fact, the economy of preventive maintenance of highway pavement, is reflected by the traffic volume of the road surface, and, in the case of maintenance, funds are limited for the maintenance of highways to accommodate the traffic volume. The economic benefits brought about by repair are more important factors to consider but must also meet the principle of the highest ratio of output to input; therefore, when considering the technical index indicators of the road surface at the same time, it is important to account for the economic benefits of preventive maintenance, so as to determine its optimal maintenance schedule. In this paper, using the basis of the framework of the whole life cycle analysis of highway pavement maintenance projects, all the benefits and costs within the analysis period are accounted for, and the cost-effectiveness ratio method is used to determine the optimal timing for the preventive maintenance of pavements.

Different life-cycle analysis methods have distinct characteristics that are suited to varying applications:

(1) Annual equal cost method. This method distributes the total production cost evenly across each year and compares the discounted costs annually. While intuitive, this approach does not align well with the practical realities of highway maintenance and management.
(2) Present value method. This method calculates the present value of expenses incurred over the life cycle using an estimated discount rate. Although it accounts for costs, it does not incorporate benefits.
(3) Net present value (NPV) method: The NPV method calculates the net value by subtracting expenses from benefits. While it reflects the total benefits, it may overvalue some projects that usually have considerably more investment.
(4) Rate of return method. This method evaluates the net cash flows over the project life cycle, with the discount rate at which the net present value equals zero defining the project's rate of return. However, this method is sensitive to large cash-flow fluctuations and does not facilitate direct comparison between projects of different scales.
(5) Cost-benefit ratio method. This method divides the present value of benefits by costs to define the benefits per unit of input-output, effectively addressing the bias caused by project scale. It enables comparisons across projects of different sizes. However, this method requires precise definitions and the calculation of benefits and costs.

In this article, the cost-benefit ratio method is employed to analyze preventive maintenance. Appropriate cost and benefit items are selected for comparison to provide a balanced and practical evaluation framework.

3. Methodology

3.1. Whole Life Cycle Theory

The whole life cycle theory originated in the U.S. military during the 1960s and expanded beyond the field of military management to other disciplines in the 1970s. A project is divided into distinct stages, with tasks and objectives clearly defined for each stage, to control costs and expenditures. These stages constitute the project's life cycle [12]. The life cycle encompasses the implementation phase of a project and its initiation and closure. These three primary stages can be further subdivided into more granular substages, including a detailed and comprehensive process that defines the full scope of the life cycle [13].

Highway disease management could prioritize maximizing total benefits across all stages of the highway's life cycle, from its opening to the end of its designed service life, with appropriate cost discounting. The characteristics of whole life-cycle highway disease management are typically as follows: (1) Long-term systematic projects. Highway disease management is a long-term, systematic endeavor requiring scientific and structured approaches. Each segmented management and maintenance activity achieves its intended objectives and desired outcomes. (2) Systematic and phased approach. The life-cycle management of highway diseases necessitates a systematic, phased methodology, making it inherently more complex than conventional pavement maintenance. This complexity arises from the need to address the various stages of the highway's life cycle comprehensively.

3.2. Life Cycle Analysis Methods

Various macro-environmental factors significantly influence the highway life cycle, and different classification criteria can decisively impact analysis and calculations. If the life cycle's duration is too short, the variations in investment and returns among the different schemes will be minimal, making it difficult to discern the comparative advantages and disadvantages of each approach. Conversely, if the life cycle is too long, increasing uncertainties can lead to significant estimation errors in costs and benefits, reducing the rigor and practical applicability of the method.

In China, the Ministry of Transportation and Communications of China's Measures for Economic Evaluation of Highway Construction Projects stipulates a 20-year period for analysis. Given the country's rapid economic and technological development, the societal changes and the long-term benefits of early maintenance interventions need to be accounted for. To adapt to these dynamic factors and ensure a realistic assessment, this article adopts a 10-year life cycle analysis period, which better reflects the current pace of development while accommodating the long-term benefits of timely highway maintenance.

3.3. Traffic Volume Forecast

To calculate the benefits of highway maintenance, it is essential to first predict the traffic volume of the highway section following maintenance. This prediction has the following characteristics:

(1) Relatively short analysis period: Traffic volume predictions are completed during the maintenance construction period, which involves a smaller workload and a shorter duration.
(2) Minimal changes in characteristics: While disease maintenance can enhance highway performance, preventive maintenance only intervenes during periods of mild

deterioration. As such, traffic volume is unlikely to show significant changes during this stage.

(3) Connectivity with other highways: Highways are part of broader transportation networks connecting with other roads. The traffic volume of a specific highway is influenced by the traffic conditions of the connected highways. Measuring traffic volume across a local transportation network is often necessary to accurately estimate the traffic volume of a single highway.

Traffic volume predictions typically rely on methods such as neural networks [14], Markov chains [15], grey prediction methods [16], and elasticity coefficient methods [17], which require relatively complete and consistent historical data. However, real-world transportation environments are highly variable and may not exhibit clear regularities.

To address these challenges, this article employs the Wardrop user equilibrium principle, using generalized costs as the objective function to establish a user equilibrium flow model [18] for predicting traffic flow changes. The generalized cost is calculated following the AASHO methodology, as outlined in Equation (1):

$$\mathrm{C}(B_n) = T_C + V_C + S_C + E_C + N_C \tag{1}$$

where $\mathrm{C}(B_n)$ is the cost of traffic volume B_n. T_C is the time cost of vehicle travel, V_C is the cost of vehicle travel, S_C is the cost of traffic safety, E_C is the cost of vehicle pollution, and N_C is the cost of vehicle noise. These four specific cost calculation formulas will be introduced in the Section 3.4.2.

The objective function of the cost is shown in Equation (2); $C_{ij}^n(Q)$ is the cost of vehicle type n running on section (i, j).

$$min\ C = \min(\sum_{i,j=1}^{m} \sum_{m=1}^{N} \int_0^{q_{ij}^n} C_{ij}^n(Q) dQ) \tag{2}$$

The constraint conditions of the user equilibrium flow model are shown in Equations (3) and (4):

$$\sum_{k=1}^{e} q_{jk}^{s,n} = D(j,s,n) + \sum_{i=1}^{m} \sum_{k=1}^{e} q_{jk}^{s,n}\ , s = 1, L, p, j = 1, L, n, j \neq s \tag{3}$$

$$V > 0,\ q_{ij}^{s,n} > 0,\ s = 1, L, p \tag{4}$$

where m is the number of nodes in the highway network; p is the number of starting and ending points; q_{ij}^n is the total flow of vehicle type n on section (i, j); $q_{jk}^{s,n}$ is the flow of vehicle type n to end point s on section (i, j); D (j, s, n) is the flow from j to s for an n-type vehicle; N is the number of vehicles; V is the maximum traffic. This model is a convex optimization model [19] and is solved with the Frank–Wolfe algorithm [20,21].

3.4. Composition of Costs

3.4.1. Highway Cost Composition and Accounting

The calculation of highway costs involved in life-cycle preventive maintenance consists of expenses related to highway management, highway users, and the environmental impact of the highway. Highway management costs include the investment and construction expenses of the highway, the costs associated with regular and preventive maintenance, and the residual value of the highway. User-related costs involve expenses incurred during travel time, vehicle operation costs, safety costs from traffic accidents, and costs associated with the highway's environmental impact. In this study, particular emphasis is placed on calculating the costs related to vehicle pollution.

(1) Residual value of the highway

Among the expenses related to highway management, the investment and construction costs of highways can be directly obtained from the relevant construction announcements. The residual value of a highway represents its remaining value relative to its designed service life. This residual value can be calculated using Equation (5):

$$FV = \frac{L_R}{L_E} \cdot C_r \tag{5}$$

in which FV refers to the residual value of the highway, where the unit is yuan (CNY); L_R refers to the service life of the highway, where the unit is years; L_E refers to the designed service life of the highway, where the unit is years; C_r refers to the construction cost of the highway, where the unit is CNY. These numbers can be obtained from the highway program plan. In addition to the costs of investment, construction, and maintenance, the costs associated with users and the impact of the highway on the environment are described in Section 3.4.2.

(2) Cost of regular maintenance

Daily maintenance cost refers to the amount required by the road maintenance management department to ensure that the pavement has good serviceability during the service life cycle and implement pavement repair program, which mainly includes the labor cost, repair material cost, machinery use cost, and so on. This paper refers to the daily maintenance cost model proposed by Sun [22], as follows:

$$C_i = 0.34 + 3.44 \times 10^{-6} \times (100 - PCI_i) \cdot ADT_i \tag{6}$$

where C_i is the maintenance cost of the i^{th} year, where the unit is CNY/square meter; PCI_i is the road condition index of the i^{th} year; ADT_i is the average daily traffic volume of the i^{th} year.

(3) Cost of preventive maintenance

Preventive maintenance costs can be estimated with reference to research findings from Indiana, USA [23]. The equation is as follows:

$$C_k = \sum_{i=1}^{n} C_t [\frac{1}{(1+i)^n}] \tag{7}$$

where C_k represents the present value of preventive maintenance costs. C_t is the cash outflow in year t; i is the discount rate.

3.4.2. User Cost Composition and Accounting

The primary benefit of highway maintenance is the reduction in road operation-related costs. According to AASHO, the benefits of highway maintenance include savings in vehicle travel time, reductions in vehicle operating costs, the prevention of traffic accidents, and decreases in vehicle pollution [24].

(1) Cost of travel time

Reduced time spent on the road allows the saved time to be contributed to other production activities, which produces greater potential value [25]. The method for calculating the cost of the time saved due to maintenance is shown in Equation (8).

$$T_c = \sum_{i=1}^{n} Q_i \cdot T_i \cdot \theta \tag{8}$$

Specifically, T_c is the vehicle travel time cost; Q_i is the traffic volume of vehicle type i; T_i is the travel time of vehicle type i; θ is the time value coefficient.

θ represents the value that may be generated per unit of time [26]. This paper refers to the method used by Zongfang et al. [27] to calculate the conversion coefficient of value, combined with the Probit model to estimate the time value considering the factors of production and income. The calculated coefficient of the time value of the traveler against personal income in the region is shown in Table 1.

Table 1. Table of correspondence between monthly personal income and the time value.

Individual Monthly Income Ranges (CNY)	Time Value Ranges (CNY/hour)
(0, 500]	(0, 2.08]
(500, 1000]	(2.08, 4.17]
(1000, 2000]	(4.17, 8.33]
(2000, 3000]	(8.33, 12.5]
(3000, 4000]	(12.5, 16.67]
(4000, 5000]	(16.67, 20.83]
(5000, 6000]	(20.83, 25]
(6000, 7000]	(25, 29.17]
(7000, 8000]	(29.17, 33.33]
(8000, 9000]	(33.33, 37.5]
(9000, ∞]	(37.5, ∞]

A function is introduced into the pavement condition index (PCI) to calculate the vehicle travel time on a highway, such as in Equation (9):

$$T = \alpha \cdot L \cdot (PCI - \eta)^{\beta} + \frac{L}{V_0} \tag{9}$$

where T is the vehicle travel time; PCI is the pavement condition index; V_0 is the maximum design speed; L is the segment mileage; α, η, and β are the pending parameters.

(2) Cost of operating vehicles

It includes expenses directly incurred from driving and depreciation, covering fuel costs, highway tolls, and expenses related to business management when commercial activities are involved. The method for calculating travel cost savings due to maintenance is presented in Equation (10).

$$V_C = \sum_{i=1}^{n} Q_i \cdot V_i \tag{10}$$

Specifically, V_C is the cost of operating vehicles; V_i refers to the vehicle operating cost of vehicle type i; Q_i refers to the traffic volume of vehicle type i.

Among the vehicle operating costs, commercial management expenses are incurred regardless of the road section or maintenance status, as they are intrinsic to the vehicle itself. Similarly, depreciation charges and highway tolls are not directly linked to road maintenance. Depreciation charges depend on the vehicle's mileage, while tolls, particularly for trucks, also correlate with carrying capacity. This paper references Akcelik R.'s research [28], defining vehicle running costs primarily through fuel consumption. Fuel consumption can be accurately determined through direct vehicle testing and engine performance measurements under real-world conditions.

The International Roughness Index categorizes the vehicles operating on roads into cars, passenger vehicles, light trucks, medium trucks, and heavy trucks, based on vehicle type [29]. The fuel consumption for each vehicle type is calculated using Equation (11).

$$Y = a_i \cdot U^2 + b_i \cdot U + c_i \tag{11}$$

where Y is fuel consumption; U is speed; i is the vehicle type; a_i, b_i, and c_i are the coefficients to be determined.

The functional relationship between speed and the flatness of each vehicle type is shown in Equation (12).

$$U = d_i \cdot \ln(IRI) + e_i \tag{12}$$

where U is speed; IRI is the international flatness index; d_i and e_i are coefficients that are yet to be determined.

The functional relationship between fuel consumption and the flatness of each vehicle type is shown in Equation (13).

$$Y = \alpha_i \cdot ln(IRI)^2 + \beta_i \cdot \ln(IRI) + \gamma_i \tag{13}$$

(3) Cost of Traffic Safety

Traffic accidents result in vehicle damage and various associated costs. These costs arise from diverse factors, including the driver's physical condition and skill level, weather conditions, road conditions, and traffic flow. Due to the random nature of these factors, traffic accidents are highly unpredictable. The consequences extend beyond disrupting highway traffic order, causing injuries, fatalities, and infrastructure damage, leading to significant economic losses for society as a whole. Traffic accidents are more likely to occur during periods of saturated traffic congestion or unstable traffic flow.

Current research on traffic accident costs often involves detailed cost decomposition. For instance, in the United States, such costs are categorized into direct and indirect costs [30]. Direct costs represent the economic loss caused by the accident itself, while indirect costs cover broader societal and individual economic impacts. In Japan, traffic accident costs are divided among those costs incurred by the involved parties, public administration, and third parties [31]. In Germany, costs are classified into those arising from losses and those related to restoration [32]. Additionally, highway users may express a willingness to pay toward mitigating the external costs caused by traffic accidents, reflecting a societal interest in minimizing these impacts [33].

The safety costs that can be saved due to maintenance are calculated in Equation (14).

$$S_C = \sum_{i=1}^{n} SC_i \tag{14}$$

Specifically, S_C is the traffic safety cost; n is the number of vehicle types; SC_i is the traffic accident cost of the i vehicle type.

The calculation of traffic safety cost refers to the standards of various countries and is divided into the medical cost C_1 of the party involved in the accident, the property loss C_2 of the party involved in the accident, the labor income loss C_3 of the party involved in the accident, and the resource expenditure C_4 of the public institution. For the loss of the third party, C_5, the calculation method should be in accordance with Equation (15).

$$SC_i = \sum_{j=1}^{5} C_j \tag{15}$$

The level of traffic accidents and the cost of accidents in the United States [34] are classified by vehicle type, including cars, passenger cars, small trucks, medium trucks, and heavy trucks. The relationship function between the number of vehicle accidents and the road's roughness is shown in Equation (16):

$$ST_i = \left[a_i^{(IRI-b_i)} + c_i\right] \cdot K \tag{16}$$

where ST_i is the number of accidents per year of the i model; a_i, b_i, c_i are the parameters to be determined; and K is the density of traffic flow.

The calculation of the annual costs due to traffic accidents on designated roads is given in Equation (17).

$$SC = \sum_{i=1}^{n} \sum_{j=1}^{m} \{[a_{ij}^{(IRI-b_{ij})} + c_{ij}] \cdot K \cdot C_j\} \quad (17)$$

where SC is the traffic accident cost, j is the accident level, and C_j is the accident cost. The calculation is as shown in Equation (13).

3.4.3. Environment Cost Composition and Accounting

The environmental impact of highway traffic comes from two sources: air pollution and noise pollution.

(1) Cost of Vehicle Air Pollution

The air pollution of vehicles mainly comes from the exhaust gases emitted after the combustion of fuel, the main pollutants of which include CO, HC, NO_X, and SO_X [35]. However, as global temperatures rise, CO_2 is also recognized as a factor affecting the environment due to highways in China [36]. The models used mainly include the EMFAC model [37], MOBILE model [38], and CMEM model [39]. The cost due to conservation can be calculated as shown in Equation (18).

$$E_C = (\sum_{i=1}^{n} Q_i \cdot E_i) \cdot P \quad (18)$$

Specifically, E_C is the saving of vehicle pollution cost; E_i is the discharge amount of type i pollutants; P is the unit cost of tailpipe gas pollution.

In this paper, we use the CMEM model [40] to calculate the economic cost caused by exhaust emission, in which CO, NO_X, and HC are selected as emission factors, and the relationship between them and road-segment driving is shown in Equation (19):

$$E = (E_{CO} + E_{NO_X} + E_{HC}) \cdot L \cdot Q \quad (19)$$

where E is exhaust emission, E_{CO} is the comprehensive emission factor of CO, E_{NOX} is the comprehensive emission factor of NO_X, E_{HC} is the comprehensive emission factor of HC, L is section length, and Q is traffic volume.

The cost of pollution that can be saved for a particular section of road is calculated in Equation (20):

$$E_C = (E_{CO} + E_{NO_X} + E_{HC}) \cdot L \cdot Q \cdot P \quad (20)$$

in which P is the unit cost of exhaust pollution, with reference to the related study by the Federal Highway Administration [41]; the latest cost is obtained by adjusting the CPI with the base year of 1992.

(2) Cost of Traffic Noise Pollution

The cost of traffic noise pollution is a measure of the level of environmental pollution caused by noise emitted by vehicle traffic that exceeds national environmental noise standards. Traffic noise pollution is a type of energy pollution belonging to the category of physical pollution, and its perceptibility, localization, and temporal characteristics make its measurement a more complex problem [42]. A large number of studies have concluded that the US Federal Highway Administration's highway traffic noise prediction model is applicable to actual road conditions in China [43,44]. The vehicle noise calculation formula is as follows:

$$Leq = 10 \cdot \lg(\sum_{i=1}^{n} 10^{0.1 \cdot Leq_i}) \quad (21)$$

$$Leq_i = L\omega_i + 10\cdot\lg\left(\frac{N_i\cdot\pi\cdot D_o}{V_i\cdot T}\right) + 10\cdot\lg\left(\frac{D_o}{D}\right)^{1+\alpha} + 10\cdot\lg\left(\frac{\psi_\alpha(\psi_1,\psi_2)}{\pi}\right) + \Delta S \quad (22)$$

where Leq is the total equivalent sound level of the road section; Leq is the total equivalent sound level of vehicle model i in the road section; n is the total number of model i vehicles; $L\omega_i$ is the average radiated sound level of vehicle model i in the calculation time T; N_i is the number of model i vehicles at a prediction point in the calculation time T; V_i is the speed of vehicle model i at a prediction point in the calculation time T; D_o is the distance from the reference position for measuring the radiated sound level of the vehicle; D is the vertical distance from the road centre line to the prediction point; α is the ground coverage coefficient, which takes the value of 0 or 0.5; ψ_α is the correction function of the finite-length road section; ψ_1 is the tensor angle from the prediction point to one end of the finite-length road section; ψ_2 is the tensor angle from the prediction point to the other end of the finite-length road section; ΔS is the attenuation caused by the shading objects.

According to Equation (9), the functional relationship between highway traffic noise and pavement condition index PCI can be obtained with the following equation.

$$Leq_i = L\omega_i + 10\cdot\lg\{\frac{N_i\cdot\pi\cdot D_o}{[\alpha\cdot(PCI-\eta)^\beta + V_0]_i\cdot T}\} + 10\cdot\lg\left(\frac{D_o}{D}\right)^{1+\beta} + 10\cdot\lg\left(\frac{\psi_\alpha(\psi_1,\psi_2)}{\pi}\right) + \Delta S \quad (23)$$

Therefore, the noise cost of vehicles on the roadway is:

$$N_C = 10\cdot\lg(\sum_{i=1}^{n} 10^{0.1\cdot Leq_i})\cdot P\cdot Q_i \quad (24)$$

where P is the unit cost of traffic noise pollution. There are fewer studies at home and abroad on accounting for the unit cost of traffic noise pollution. In this paper, the unit cost of traffic noise pollution is calculated with reference to the noise reduction cost method, as shown in Equation (25):

$$P = \frac{C}{\left(Leq_{before} - Leq_{after}\right)\cdot L} \quad (25)$$

where C is the noise reduction cost; L is the length of the noise reduction section; Leq_{before} is the noise equivalent level before noise reduction; Leq_{after} is the noise equivalent level after noise reduction.

3.5. The Model for Determining Preventive Maintenance Time

In existing research on preventive maintenance [45–47], the timing of implementation is primarily determined by the technical parameters of the road surface and the impact of passing vehicles. Maintenance is typically carried out when the road surface parameters deteriorate to a level that affects vehicle traffic. However, the role of highways extends beyond enabling vehicle passage.

As a result, highway maintenance could prioritize economic considerations. Analyzing only the technical parameters of the road surface fails to account for changes in traffic volume, which are directly tied to economic outcomes. The economic benefits of preventive maintenance are reflected in the preservation of or even increase in traffic volume. Given budgetary constraints, highway operations and management could ensure that every expenditure delivers sufficient economic returns. This requires achieving the highest input-output ratio and executing maintenance decisions at the most optimal time.

It is equally important to measure the economic benefits derived from preventive maintenance. This article adopts the cost-effectiveness ratio to determine maintenance timing within the framework of a highway's entire life cycle, which focuses on the costs and benefits incurred during the maintenance accounting period.

3.5.1. Assumptions

According to the theory of the entire life cycle, appropriate preventive maintenance strategies could be established during the construction and early operation of highways to effectively manage highway diseases. We focus on selecting maintenance strategies for the first 10 years of highway operation, implementing preventive maintenance after t years of use. By calculating the various costs and benefits that influence highway operation, the goal is to maximize cost-effectiveness in managing highway diseases over the highway's life cycle and optimize its utilization efficiency.

Preventive maintenance is applied while the road surface remains functional. To align with real-world conditions, the following assumptions are made:

(1) Post-maintenance performance: The technical performance of the road surface meets normal usage standards after preventive maintenance.
(2) Pre-maintenance condition: Before preventive maintenance, the road has no severe damage or diseases. Severe road diseases, if present, require corresponding repairs.
(3) Traffic flow flexibility: Vehicles can freely select their routes within the highway network, based on current traffic conditions.
(4) Unaffected toll rates and capacity: Preventive maintenance does not impact highway toll rates or maximum traffic capacity.

These assumptions aim to ensure the realistic application of preventive maintenance strategies and provide a framework for achieving optimal highway performance and cost efficiency.

3.5.2. Cost Calculation in the Life Cycle

The highway's life cycle is assumed to span 10 years, starting from the time it is put into service. Preventive maintenance is conducted once, at most, in its whole life. Following each maintenance activity, the various usage costs of the road are minimized, gradually increasing as diseases re-emerge, as is shown in Figure 1.

For preventive maintenance conducted in year t after the road's opening, the total costs before and after maintenance up to year 10 are calculated separately. The calculation method is presented in Equation (26):

$$C = \sum_{i=1}^{t-1} [c_2(Q_i) + c_3(Q_i)] \cdot (1+r)^{1-t} + \sum_{i=t}^{10} [c_2(Q_i) + c_3(Q_i)] \cdot (1+r)^{10-t} + c_{11} + (c_{12} + c_{13} - RV) \cdot (1+r)^{-t} \quad (26)$$

where C is the cost of the whole life of a highway, which includes the maintenance-related cost; t is the opening time when preventive maintenance is implemented; C_2 (Q_i) is the function of the user cost in year i with respect to the volume of traffic. C_3 (Q_i) is the functional relationship of environmental cost with respect to traffic volume in year i, and the functional relationship of cost with respect to traffic volume in these two items is the sum of the functional relationship of each vehicle type with respect to traffic volume in Equation (1); c_{11} is the construction cost. c_{12} is the regular maintenance cost, c_{13} is the preventive maintenance cost, and RV is the residual value; these three items form the highway management-related cost, and r is the discount rate. The construction cost of the highway can be directly obtained by examining the relevant announcements; the pavement maintenance cost refers to the average value of the historical data for a highway of the same grade, and the user cost includes travel time cost, vehicle cost, and traffic accident cost. These are calculated with Equations (7), (11) and (15), respectively. Environmental expenses from vehicle pollution costs are calculated with Equation (17).

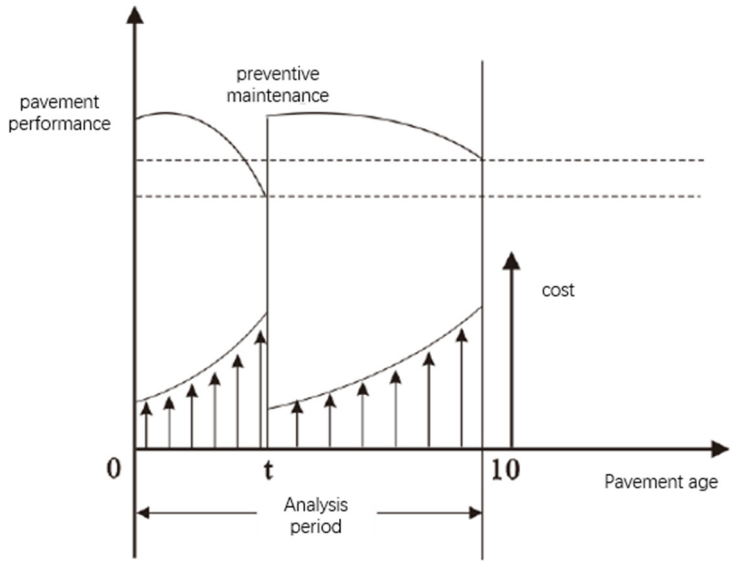


Figure 1. Cost changes of preventive maintenance in the life cycle.

3.5.3. Benefits Calculation in the Life Cycle

Theoretically, the essence of rationalizing the timing of preventive maintenance implementation is how to assess the benefits of the pavement pre-maintenance. The preventive maintenance of pavements brings many benefits to the highway sector and its users, including a reduction in the number of accidents, shorter traveling time, lower vehicle operating costs, savings in maintenance costs, reduced interference with the work of nearby businesses, increased driving comfort, and increased public satisfaction. The benefits derived from these measures mainly come from the improvement of pavement performance, so the benefits of preventive maintenance measures can be comprehensively characterized by the area enclosed by the pavement performance curve and the baseline of the minimum acceptable level of benefits, which is called the area of benefits.

When pre-maintenance measures are applied, the increment of this benefit area is called the pre-maintenance benefit area. The daily maintenance benefit area and pre-maintenance benefit area are A_d and A_j, as shown in Figure 2. Time zero is the initial time of a new pavement's construction or major or moderate repair. In Figure 2, $y = f_d(x)$ is the index decay curve regarding daily maintenance, and $y = f_j(x)$ is the equation of the expected decay curve after pre-maintenance measure j is taken at moment x_{j0}; y_{j0} is the minimum acceptable level line for the benefit calculation; x_d is the intersection of the pavement performance curve $y = f_d(x)$ and the minimum acceptable level line y_{j0} under daily maintenance; x_j is the intersection of the pavement performance curve $y = f_j(x)$ and the minimum acceptable level line y_{j0} after preventive maintenance is taken, which is the termination time point of the benefit calculation.

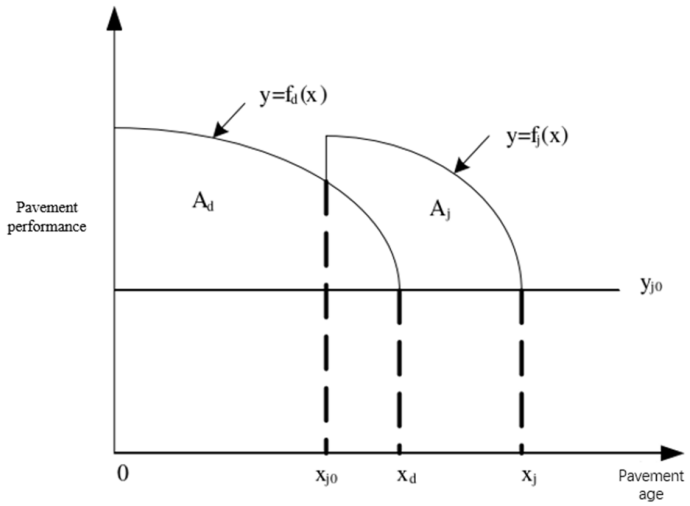


Figure 2. Calculation of the benefits of a single indicator in preventive maintenance.

Preventive conservation measures generally result in multiple performance improvements at the same time; thus, benefit analyses often need to consider the benefit contributions of multiple indicators at the same time. In this case, it is necessary to determine the area of benefit for each of the different indicators. The calculation of the benefit area of multiple indicators is basically the same as that of a single indicator; the difference is that the termination point of the benefit area calculation is not the intersection of the decay curves of each indicator and the lowest acceptable level, but instead the minimum of all intersection points x_{d1j} and x_{j1i}, i.e., $x_{d1} = \min x_{d1i}$, $x_{j1} = \min x_{j1i}$, as is shown in Figure 3.

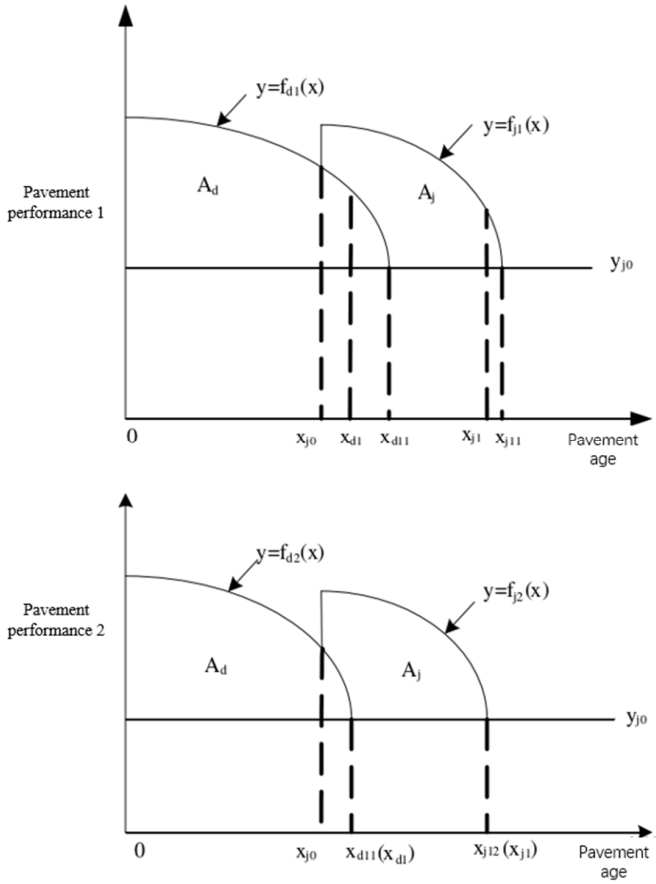


Figure 3. Calculation of the benefits of multiple indicators in preventive maintenance.

In order to combine the benefits derived from multiple indicators, the area of benefits from each indicator that is analyzed can be standardized and then weighted. The weighted comprehensive value of the preventive maintenance benefit is called the preventive maintenance benefit index or PBI, for which the calculation formula is as follows:

$$PBI_j = \sum_{i=1}^{n} \alpha_i \frac{A_{ij}}{A_{id}} \quad (27)$$

where PBI_j is the preventive maintenance benefit index of the j^{th} maintenance time; α_i is the effect weight coefficient of the i^{th} index, the value of which can be obtained by the AHP method; A_{ij} is the area of benefit of the ith index at the j^{th} maintenance time, after adopting preventive maintenance measures; A_{id} is the area of benefit of the ith index under daily maintenance; n is the number of preventive maintenance benefit analysis indicators.

3.5.4. Optimum Maintenance Time

The decision-making method for implementing preventive maintenance is to calculate the ratio of the benefits and costs of implementing preventive maintenance in year t to the whole life cycle of the highway, according to the above formula, and to rank them in chronological order. The timing scheme with the largest ratio of benefit-to-cost is the best option:

$$\mathrm{T} = Maximize\{\frac{B_t}{C_t}\} \quad (28)$$

where T is the optimal time for the preventive maintenance of highway pavements; B_t is the life-cycle benefit generated by implementing preventive maintenance at pavement age t; C_t is the life-cycle cost generated by implementing preventive maintenance at pavement age t.

4. Case Study

4.1. Introduction to the Dataset

Consider a highway in XI City as an example, with a total length of 230.26 km and an investment of CNY 3.64 billion. It is assumed that only one preventive maintenance activity will be conducted within the 10 years following the highway's commissioning. This maintenance is performed at the beginning of the year, restoring the technical characteristics of the pavement to its ideal condition, a state equivalent to when the highway was first put into service. The basic data for a specific section of the highway, both before and after maintenance, are collected and presented in Table 2. Since highway pavement conditions are typically assessed annually, this article uses a one-year time unit for calculating the cost.

Table 2. Highway pavement condition index and vehicle flow of each vehicle type before and after maintenance.

Indicators	Pre-Maintenance	Post-Maintenance
PCI	68	89
IRI	0.66	0.83
Section mileage (km)	38.6	38.6
Maximum design speed (km/h)	120	120
Minibus	3.834×10^7	3.941×10^7
Coach	0.501×10^7	0.529×10^7
Heavy truck	0.339×10^7	0.362×10^7
Medium truck	0.778×10^7	0.821×10^7
Light truck	0.611×10^7	0.652×10^7

4.2. Parameter Estimation

(1) Cost of travel time

The non-parametric form of this formula is determined using the data of the 5000 vehicles on the road that were entered into Equation (9) for use in Equation (29).

$$T = 0.001 \cdot L \cdot (PCI - 0.3)^{-0.018} + \frac{L}{V_0} \tag{29}$$

The time value coefficient is taken as 15.32. The cost is CNY 7.466×10^7, derived from vehicle travel time.

(2) Cost of operating vehicles

The vehicle operating cost mainly comprises fuel consumption. By fitting the experimental data of the different types of sample vehicles on the road section, the functional relationship between fuel consumption and the flatness of each vehicle type is obtained, as shown in Table 3.

Table 3. Calibration of fuel consumption parameters.

Model	Fuel Consumption Function
Minibus	$Y = \left[0.019 \cdot \ln(IRI)^2 - 0.008 \cdot \ln(IRI) + 0.059\right]$
Coach	$Y = \left[0.013 \cdot \ln(IRI)^2 - 0.012 \cdot \ln(IRI) + 0.288\right]$
Heavy truck	$Y = \left[0.034 \cdot \ln(IRI)^2 - 0.022 \cdot \ln(IRI) + 0.351\right]$
Medium truck	$Y = \left[0.024 \cdot \ln(IRI)^2 - 0.021 \cdot \ln(IRI) + 0.306\right]$
Light truck	$Y = \left[0.019 \cdot \ln(IRI)^2 - 0.023 \cdot \ln(IRI) + 0.278\right]$

Assuming that the price of 0 # diesel oil is CNY 7.8/L and the price of 92 # gasoline is CNY 8/L, the vehicle operating cost is calculated as CNY 1.183×10^8, according to the fuel consumption function.

(3) Cost of traffic safety

Table 4 shows the nominal values of the function parameters for the number of accidents of each vehicle type.

Table 4. Safety accident parameter calibration.

Model	Functional Relationship Formula		
	Fatal Accident	Injury Accident	Property Damage Incidents Only
Minibus	$SC = \left[0.686^{(IRI-0.3)} + 1.014\right] \cdot K$	$SC = \left[0.773^{(IRI-0.3)} + 1.545\right] \cdot K$	$SC = \left[0.741^{(IRI-0.3)} + 1.978\right] \cdot K$
Coach	$SC = \left[0.678^{(IRI-0.3)} + 1.121\right] \cdot K$	$SC = \left[0.681^{(IRI-0.3)} + 1.262\right] \cdot K$	$SC = \left[0.715^{(IRI-0.3)} + 1.337\right] \cdot K$
Heavy truck	$SC = \left[0.779^{(IRI-0.3)} + 1.031\right] \cdot K$	$SC = \left[0.813^{(IRI-0.3)} + 1.837\right] \cdot K$	$SC = \left[0.821^{(IRI-0.3)} + 2.155\right] \cdot K$
Medium truck	$SC = \left[0.687^{(IRI-0.3)} + 0.932\right] \cdot K$	$SC = \left[0.711^{(IRI-0.3)} + 1.346\right] \cdot K$	$SC = \left[0.747^{(IRI-0.3)} + 1.619\right] \cdot K$
Light truck	$SC = \left[0.736^{(IRI-0.3)} + 0.835\right] \cdot K$	$SC = \left[0.742^{(IRI-0.3)} + 1.506\right] \cdot K$	$SC = \left[0.753^{(IRI-0.3)} + 1.516\right] \cdot K$

Referring to the functions in the table, CNY 1.193×10^7 is the traffic safety cost.

(4) Cost of vehicle air pollution

Working according to the experimental data, the emission factor function corresponding to each vehicle type is shown in Table 5.

Table 5. Parameter calibration of the comprehensive emission factor of tailpipe gas.

Model	Comprehensive Emission Factor Function of Tailpipe Gas
Minibus	$E_{CO} = 55.32 - 6.274 \cdot PCI - 5.43 \cdot PCI^2 - 4.55 \cdot PCI^3$ $E_{NO_X} = 2.16 - 0.27 \cdot PCI - 0.55 \cdot PCI^2 - 0.39 \cdot PCI^3$ $E_{HC} = 3.47 - 2.59 \cdot PCI^{0.31}$
Coach	$E_{CO} = 86.327 - 5.62 \cdot PCI - 8.59 \cdot PCI^2 - 6.33 \cdot PCI^3$ $E_{NO_X} = 3.22 - 0.27 \cdot PCI - 0.61 \cdot PCI^2 - 0.42 \cdot PCI^3$ $E_{HC} = 5.27 - 2.91 \cdot PCI^{0.26}$
Heavy truck	$E_{CO} = 73.42 - 7.28 \cdot PCI - 3.13 \cdot PCI^2 - 4.08 \cdot PCI^3$ $E_{NO_X} = 12.29 - 0.34 \cdot PCI - 0.55 \cdot PCI^2 - 0.49 \cdot PCI^3$ $E_{HC} = 9.85 - 2.47 \cdot PCI^{0.32}$
Medium truck	$E_{CO} = 68.71 - 8.62 \cdot PCI - 5.34 \cdot PCI^2 - 2.72 \cdot PCI^3$ $E_{NO_X} = 2.19 - 0.47 \cdot PCI - 0.43 \cdot PCI^2 - 0.38 \cdot PCI^3$ $E_{HC} = 4.97 - 2.91 \cdot PCI^{0.38}$
Light truck	$E_{CO} = 55.28 - 6.22 \cdot PCI - 5.49 \cdot PCI^2 - 4.59 \cdot PCI^3$ $E_{NO_X} = 2.23 - 0.27 \cdot PCI - 0.54 \cdot PCI^2 - 0.33 \cdot PCI^3$ $E_{HC} = 3.49 - 2.66 \cdot PCI^{0.31}$

This paper refers to the calculation of the environmental pollution cost caused by automobile exhaust in the United States in 2015, and the cost of pollution caused by automobile exhaust, as adjusted by the exchange rate. The calculated pollution cost of automobile exhaust can save CNY 3.592×10^7 after pavement maintenance.

(5) Cost of vehicle noise pollution

According to the actual test values of the samples, with calibrated parameter values of α = 0.001 and β = 0.251, these were estimated to yield a cost of CNY 4.124×10^5 for traffic noise pollution on the road.

(6) Parameters of the derived benefits

In the Chinese 'Highway Technical Condition Assessment Standards' for asphalt pavement, pavement damage, road smoothness, pavement rutting, skid resistance, and structural strength provide five technical indicators, all of which appear in the pavement performance index (PQI) to comprehensively represent the overall performance of the pavement. The formula is shown in Equation (30).

$$PQI = 0.29 \times PCI + 0.26 \times ROI + 0.17 \times RDI + 0.15 \times SRI + 0.13 \times PSSI \quad (30)$$

Based on the measured data from another nearby motorway, the values of the pavement damage condition index (PCI), the ride quality index (RQI), the rut depth index (RDI), the pavement skid resistance index (SRI), the pavement strength index (PSSI), and the pavement serviceability index (PQI) were calculated and are shown in Table 6.

Table 6. Data for pavements before preventive maintenance measures are taken.

Years of Use	PCI	RQI	RDI	SRI	PSSI	PQI
1st year	98.7	96.68	95.7	97.89	98.7	97.36
2nd year	94.31	96.23	94.9	94.57	97.6	95.19
3rd year	90.7	95.79	93.4	91.35	96.63	93.21
4th year	87.9	94.89	91.8	88.04	95.57	91.30
5th year	85.5	93.62	89.26	84.93	94.29	89.26

Based on the PQI values obtained from the above calculations, a regression prediction model was used to predict the values of the PQI for the following eight years. The results of this prediction are presented in Table 7.

Table 7. Prediction values for PQI.

Years of Use	Original Value	Prediction Value
1st year	97.36	97.27
2nd year	95.19	95.23
3rd year	93.21	93.22
4th year	91.30	91.24
5th year	89.26	89.29
6th year		87.37
7th year		85.47
8th year		83.61
9th year		81.77
10th year		79.96
11th year		78.18
12th year		76.42
13th year		74.69
14th year		79.98

Preventive maintenance applies the appropriate treatments to delay pavement damage and maintain or improve pavement performance for the purpose of extending road service life. Based on the data collected from the nearby sections of this motorway when thin slurry sealing was adopted as a preventive maintenance measure, the empirical regression method was used to predict the decay of PQI after adopting thin slurry sealing as a maintenance measure, as shown in Table 8. Considering that the attenuation is small in the first two years, the calculations start from the third year.

Table 8. Curve equations of PQI after taking preventive maintenance measures at different ages.

Years of Use	PQI Decay Curve Equation
3rd year	$y = -0.359x^2 - 0.358x + 93.89$
4th year	$y = -0.357 - 0.356x + 93.29$
5th year	$y = -0.355x^2 - 0.355x + 93.49$
6th year	$y = -0.356x^2 - 0.345x + 93.34$
7th year	$y = -0.345x^2 - 0.425x + 93.14$
8th year	$y = -0.356x^2 - 0.346x + 92.98$
9th year	$y = -0.357x^2 - 0.341x + 92.78$
10th year	$y = -0.358x^2 - 0.361x + 92.37$

The area of effect after adopting thin slurry sealing measures at different times is shown in Table 9.

Table 9. Calculation of the area of effect after taking preventive measures.

Year	3	4	5	6	7	8	9	10
Area of performance	121.328	124.209	125.300	124.789	120.842	118.901	116.839	111.614

5. Results

5.1. Calculation of Costs and Benefits

Assuming that preventive maintenance can be carried out in any year of the road traffic period $t \in [2, 10]$, nine schemes of maintenance times can be obtained. The specific composition of the lifetime costs is shown in Table 10.

Table 10. Calculation of the present value of expenses produced by maintenance plans in each year (Unit: RMB 100 million).

Preventive Maintenance Timing	Construction Cost	Curing Expenses ($\times 10^{-3}$)	Residual	Time Cost	Driving Expenses	Security Expenses	Environment Expenses
3rd year	36.4	1.01	34.580	38.123	56.593	6.796	14.075
4th year	36.4	1.18	33.973	35.894	56.104	7.074	13.056
5th year	36.4	1.90	33.367	30.645	44.662	6.273	11.796
6th year	36.4	2.70	32.760	27.860	52.375	7.457	13.316
7th year	36.4	3.37	32.153	28.842	48.449	7.567	14.924
8th year	36.4	4.17	31.547	34.087	52.788	6.884	15.184
9th year	36.4	5.35	30.940	38.123	59.403	6.374	16.076
10th year	36.4	6.28	30.333	38.679	58.842	6.901	16.839

The total area without maintenance measures was used as the denominator so that when carrying out the benefit analysis, the area of effect was comparable between the different maintenance programs. The benefits of each program were calculated, as shown in Table 11.

Table 11. Calculation of the benefits of preventive maintenance measures.

Year	3	4	5	6	7	8	9	10
Benefit (%)	28.484	31.228	33.313	31.679	30.842	27.901	18.839	16.625

5.2. Determining the Best Time for Maintenance

See Table 12 for the calculation results of the overall cost-benefit ratio during the pavement's life cycle.

Table 12. The life-cycle cost-benefit ratio of each maintenance opportunity scheme (Unit: RMB 100 million).

Preventive Maintenance Timing	Composite Value of Benefits	Total Expenses	Benefits/Expenses (10^{-2})
3 years	28.484	118.417	24.054
4 years	31.228	115.735	26.982
5 years	33.313	98.309	33.886
6 years	31.679	107.348	29.511
7 years	30.842	107.399	28.712
8 years	27.901	117.966	23.652
9 years	18.839	130.786	14.404
10 years	16.625	133.608	12.443

As shown in Table 8, the benefit-to-cost ratio for preventive maintenance reaches its highest point, 33.886, in the fifth year after the highway's construction and opening. Hence, the optimal timing for implementing preventive maintenance is in the fifth year after the highway becomes operational.

By analyzing the trend of the benefit-to-cost ratio, it is evident that when preventive maintenance is conducted before the fifth year, the ratio gradually increases, indicating that the maintenance is implemented too early. Conversely, after the fifth year, the benefit-to-cost ratio begins to decline, suggesting that maintenance is implemented too late.

This phenomenon occurs because, immediately after construction, the highway pavement is in excellent condition and yields optimal performance. Over time, however, pavement conditions deteriorate progressively, following the natural decay pattern, which explains the variation in the benefit-to-cost ratio based on the timing of maintenance.

6. Conclusions

The management of highway diseases preserves highway performance and enables long-term usability. Effectively determining maintenance schedules throughout the entire life cycle of highway use is key to reducing or delaying the occurrence of highway diseases. To address gaps in previous research, which has focused on the technical benefits of maintenance while overlooking its economic benefits, this article analyzes the various costs incurred during highway usage. Using a life-cycle analysis approach, it compares cost-benefit ratios to identify the optimal decision-making plan for preventive maintenance, using the appropriate method to estimate each of the indirect economic factors. The findings highlight that the rationality of maintenance timing can be illustrated through specific examples. Maintenance benefits tend to increase when performed earlier and the benefits diminish with delayed maintenance. Conversely, the relationship between maintenance costs and timing is inverse, with costs rising as maintenance is postponed. This study provides a framework for optimizing preventive maintenance to achieve a balance between timing, costs, and benefits. For practical applications, we found that cost savings in terms of safety and pollution accounted for nearly 20% of the total cost savings on a 10-year average. Considering that vehicle ownership is increasing and motor technology is developing slowly, the travel-time cost and driving cost can hardly provide effective savings. Thus, safety and environmental costs will be the main focus of highway maintenance benefits. With advancements in technology, future studies could explore the more indirect benefits with a more accurate assessment of the economic impacts of highway maintenance. As demands increase, it may also become necessary to develop calculation methods that determine the optimal timing for multiple maintenance cycles over an extended highway lifespan.

Author Contributions: Writing—review and editing, A.W., F.L. and S.C.; supervision, L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the General Program of the National Natural Science Foundation of China (No.72071194) and the program of MOE Social Science Laboratory of Digital Economic Forecasts and Policy Simulation at UCAS (No. E2810801).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We thank the editors and the reviewers for their constructive comments that significantly helped improve this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

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