Research on Highway Maintenance and Management Cost Based on Life Cycle Cost Analysis

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Abstract. With the rapid development of China's highway construction, the huge demand for funds and the lack of financial strength of the contradiction is increasingly obvious, can effectively control the maintenance costs, highway operators to obtain sustainable development advantages of the key factors. This paper measures the highway maintenance and management costs including carbon emission costs based on the perspective of life cycle cost analysis. Based on the perspective of life cycle cost analysis, prediction models are developed for each component cost of highway maintenance and management costs. The carbon emission costs generated during the operation duration of highways are also included in the life-cycle costs, and the calculation model is proposed for the strategy of "30·60 carbon target" in China. In the example analysis, the carbon emission cost of new energy vehicles is only 3/4 of that of fuel vehicles in the driving phase; more than 90% of the carbon emission is generated by the driving vehicles.

1. Introduction

China's highway network has been gradually improved, however, with limited maintenance funds, maintenance has become more important in highway management.

The life cycle maintenance and management cost of highway mainly includes maintenance cost, management cost, some highway agencies consider the user cost[1]. Prediction of sub-cost is important in the study of life cycle cost of highway. Methods for predicting maintenance costs include regression analysis, grey model method, artificial neural network method[2], genetic algorithm[3], etc. Factors considered include traffic volume, speed[3] and level of economic development[2].

The management cost of highway is closely related to economic factors such as the rise of employee wages, and the commonly used prediction methods include ARMR model and regression analysis.

At the same time, more and more studies at home and abroad have begun to incorporate environmental costs into the life cycle cost of the highway for energy saving and emission reduction[4,5,6]. However, there are more studies on the carbon emissions and fewer studies on the measurement of carbon emission costs.

In this paper, on the basis of the above results, a highway life cycle maintenance and management cost measurement and prediction model that considers the carbon emission cost is established to analyse and predict the maintenance and management cost of highways, which is conducive to the highway maintenance enterprises to control the maintenance and management cost and optimize the maintenance program. The results can provide scientific decision-making support for highway cost control.

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2. Highway life cycle maintenance and management cost study

2.1. Life Cycle Cost Analysis Theory

Life cycle cost, which refers to all the costs incurred in the whole process of a product from its creation to its demise, has been fully applied in the fields of industrial products, construction and so on. The life cycle cost analysis method is multi-dimensional, quantitative AND comprehensive, which has a strong suitability with the research purpose of this paper.

The maintenance and management costs of highways can be divided into maintenance costs, management costs, and environmental costs.

2.2. Highway maintenance cost analysis

This paper divides highway maintenance cost into overhaul cost and maintenance cost other than overhaul cost, prediction model is established respectively.

2.2.1 Predictive model of maintenance costs other than overhaul costs

The influence mechanism of highway maintenance cost is very complex, but it is generally characterized by temporality and periodicity. Gray Model (GM) can make predictions for a complex system with known information and uncertainties at the same time, and it has less demand for model data, and the prediction results are not only accurate, but also reflect the actual situation of the system, which is very consistent with the needs of this study, so this paper adopts the GM to predict the development trend of highway maintenance cost.

(1) Theoretical basis of GM

GM is a kind of model for prediction in gray system. Among them, the gray time series prediction model is constructed by using the time series reflecting the characteristics of the prediction object, which is very suitable for the prediction research of highway maintenance cost with temporal characteristics.

(2) GM(1,1)Model

The GM (1,1) model is a commonly used gray prediction model, and the model steps are as follows: firstly, the known maintenance cost data $X^{(0)}$ is used as the input sequence, and $X^{(1)}$ is used as the generated sequence.

Let the original maintenance cost sequence $X^{(0)}$ be a non-negative sequence, as shown in equation (1), and $X^{(1)}$ is called the 1-AGO (one time cumulative) sequence of $X^{(0)}$), as shown in equation (2).

$$X^{(0)} = (x^{(0)}(1), x^{(0)}(2), ..., x^{(0)}(n)) \quad (1)$$

$$X^{(1)} = (x^{(1)}(1), x^{(1)}(2), ..., x^{(1)}(n)) \quad (2)$$

$$x^{(1)}(i) = \sum_{m=1}^{i} x^{(0)}(m) \quad (3)$$

Equation (4) is developed based on the obtained generating sequence $X^{(1)}$, which is called the vernacular equation of the GM(1,1) model.

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b \quad (4)$$

The time response function is :

$$\hat{x}^1(i+1) = (x^0(1) - \frac{b}{a})e^{(-ai)} + \frac{b}{a} \quad (5)$$

(3) Model applicability conditions

According to the expression of GM (1,1), equation (6) is obtained.

$$x^0(i) = (\frac{(1-0.5a)}{(1+0.5a)})^{(i-2)}(\frac{(b-ax^0(1))}{(1+0.5a)}), i = 2,3,...,n \quad (6)$$

From equation (6), $x^0(i)$ satisfies the requirement of non-negativity only when |a|<2, and the range of applicability of the model varies for different values of a. For the development coefficients -a ∈ (0, 2), in general, the range of applicability of the model can be determined according to Table 1[7]:

Table 1. Scope of application of the model corresponding to different development factors

Range of -a	Scope of application of the model
-a<0.3	medium and long-term prediction
0.3⩽-a<0.5	Short-term prediction
0.5⩽-a<0.8	Not applicable to short-term prediction
0.8⩽-a<1	The GM(1,1) correction model should be used
-a>1	Not applicable to GM(1,1) model

(4) Residual test

$$\varepsilon^{(0)} = (\varepsilon(1), \varepsilon(2), ..., \varepsilon(n)) \quad (7)$$

$$\overline{\varepsilon}^{(0)} = \frac{1}{n}\sum_{i=1}^{n}\varepsilon(i) \quad (8)$$

$$S_1{}^2 = \frac{1}{n}\sum_{i=1}^{n}\left(\varepsilon(i) - \overline{\varepsilon}^{(0)}\right)^2 \quad (9)$$

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n}x^{(0)}(i) \quad (10)$$

$$S_2{}^2 = \frac{1}{n}\sum_{i=1}^{n}\left(x^{(0)}(i) - \overline{x}\right)^2 \quad (11)$$

$$C = \frac{S_1}{S_2} \quad (12)$$

$$p = p \mid \varepsilon(i) - \overline{\varepsilon}^{(0)} \mid < 0.6745 S_1 \quad (13)$$

$\varepsilon^{(0)}$is residual sequence, $\overline{\varepsilon}^{(0)}$ is the mean value of residuals, $S_1{}^2$ is residual variance， $\overline{x}$ is mean of raw data, $S_2{}^2$ is raw data variance, C is posteriori difference in scale (math.)， p is small error probability.

The prediction accuracy level of the model is determined by a combination of the posteriori difference in scale (math.) and small error probability, as shown in Table 2.

Table 2. Model Accuracy Level

Accuracy Level	Small error probability p	The posteriori difference in scale (math.)
good	>0.95	≤0.35
qualified	>0.8	≤0.50
Barely good	>0.7	≤0.65
unqualified	≤0.7	>0.65

2.2.2 Predictive model of overhaul costs

Due to the complexity of the influencing factors of overhaul cost and the difficulty of prediction, this paper will introduce the overhaul cost model established in the literature8] to measure the overhaul cost.

$$Y = 17 \times K_1 \times (3.873 + 0.386X_1 + 1.965 \times 10^{(-4)} X_2 + 6.157X_3 - 2.639X_4 - 2.576X_5) \times (\frac{K_2}{100})^{(t-2007)} \quad (14)$$

2.3. Highway management cost analysis

Highway management cost refers to the non-productive costs required to maintain the highway, which is mainly divided into personnel expenditures and daily utility expenditures, and it tends to be linear or stepwise, so regression analysis is selected to predict the management and management cost of the highway.

This paper selects opening time as independent variable, and the regression prediction model between it and the management cost of the highway is established to predict the management cost of the highway.

2.4. Highway environmental cost analysis

2.4.1 Introduction to environmental cost methodology

To measure the cost of carbon emissions, it is necessary to obtain carbon emissions. For the calculation of carbon emissions, the more commonly used method is the emission factor method, which is calculated from the carbon content of fuels or materials, and can also be obtained by consulting the relevant carbon emission factor documents issued by provinces.

The calculation principle of the emission factor method is shown in equation (15).

$$AE = AD \times EF \tag{15}$$

Where AE is CO_2 emissions, AD is Carbon dioxide emission activity data, EF is emission factor.

Then equation (16) can measure carbon emission cost.

$$e = AE \times C \tag{16}$$

Where e is carbon emission cost (RMB), C means Carbon trading unit price (RMB/t).

2.4.2 Modelling of highway environmental cost

The main sources of carbon emissions of maintained highways are road materials and mechanical facilities, vehicles also produce a large amount of carbon dioxide due to the consumption of fossil fuels, which is the most important source of carbon emissions during the management of highways. In this paper, we will calculate and model the carbon emission costs generated by the production, processing, transportation, transport, operation of machinery and equipment, and vehicle driving during road maintenance operations.

(1) Carbon costs incurred by the moving vehicles

The quality of carbon dioxide incurred by moving vehicle is closely related to the amount of fuel consumed by the vehicle, which is closely related to the driving quality, therefore, the carbon emissions during the driving phase of a vehicle need to be calculated based on the relationship between the fuel consumption of the vehicle and the driving quality.

The International Roughness Index (IRI) can characterize driving quality of pavement, which is a commonly used performance index when conducting pavement performance evaluation. This paper introduces the fuel consumption-IRI model for different types of vehicles established by Peng[9] as a basis to calculate carbon emissions generated by moving vehicles.

The unit cost of carbon emissions generated by moving vehicles is:

$$e_{m1} = \frac{\left(F_{cm} \times F_i \times C \times \rho_i\right)}{1000} \tag{17}$$

$$F_i = C_i \times \alpha_i \times \rho \tag{18}$$

Where e_{m1} is unit cost of carbon emission from vehicle type m, F_{cm} is amount of fuel consumed per kilometre for vehicle type m, ρ_i is density of fuel i, F_i is carbon emission factor of fuel i, C_i is carbon content per unit calorific of fuel i, α_i is carbon oxidation rate of fuel i, ρ is ratio of molecular weight of carbon dioxide to carbon.

(2) Carbon emission cost from the maintenance phase

Carbon emissions generated in the road maintenance phase mainly come from the production and processing of road maintenance materials, transportation and mechanical construction. This part of the carbon emissions is still calculated using the emission factor method, and the formula for calculating the cost of carbon emissions generated during the road maintenance phase is shown in equation (19).

$$C_M = C_P + C_Q + C_C \tag{19}$$

$$C_P = \sum_{m=1}^{p} P_p \times M_p \times C \tag{20}$$

$$C_Q = \sum_{j=1}^{Q} V_q \times P_q \times L_q \times C \tag{21}$$

$$C_C = \sum_{k=1}^{C} V_c \times P_c \times T_c \times C \tag{22}$$

Where C_M is total carbon emissions cost of the road maintenance phase, C_P is carbon emission costs incurred during the production phase of road maintenance materials, C_T is carbon emission costs incurred during the transportation phase of road maintenance materials, C_C is carbon emission costs from the construction phase of road maintenance works, M_p is amount of road maintenance material p, P_p is emission factor of road material p, V_q is amount of fuel q, P_q is emission factor of fuel q for transportation, L_q is the length of transportation, V_C is amount of fuel used per unit of time for machinery c, T_C is using time of machinery c, P_c is the emission factor of fuel machine c used.

3. Highway maintenance cost prediction model based on life cycle cost analysis

In this section, Highway F in Guangdong Province is chosen as an example for the analysis of its maintenance and management costs over its entire life cycle.

3.1. Life cycle maintenance costs

3.1.1 Maintenance costs other than overhaul costs

The whole line of Highway F contains 4.227km of bridges, and because the design service life of bridges is long, it is difficult to predict bridge maintenance cost, so this paper simplifies the prediction model of bridge maintenance cost. Based on the bridge maintenance cost data of Highway F from 2010 to 2019, combined with the consumer price index of Guangdong Province in the calendar year, the bridge maintenance cost from 2010 to 2019 is discounted to 2023, and the average value is 10.631 million yuan/year; and then, using the average value of the consumer price index of Guangdong Province in the calendar year, discounting the bridge maintenance cost of future years to 2023, the average maintenance cost of bridges along the whole line can be obtained as 35.54 million yuan/year.

Road maintenance cost (except bridge maintenance cost) for highway F from 2010 to 2019 is shown in Table 3.

Table 3. Historical road maintenance costs for Highway F (in millions of dollars)

Year	Actual Value	Year	Actual Value
2010	1319.0	2015	893.2
2011	970.8	2016	971.4
2012	775.0	2017	1160.1
2013	758.8	2018	1178.8
2014	948.0	2019	1358.1

Prediction model is obtained as equation (23).

$$\hat{x}^1(i+1) = 11590.113e^{0.0638i} - 10271.113 \quad (23)$$

The prediction model was used to forecast the data from 2010 to 2019 and the predicted values were compared with the actual values, the results are shown in Table 4.

Table 4. Results of comparison of projected and actual values from 2010 to 2019

Year	Actual Value	predicted value	Residual	Relative error
2010	1319.0	1319.0	0.0	0.0%
2011	970.8	763.5	207.2	21.3%
2012	775.0	813.8	-38.8	-5.0%
2013	758.8	867.5	-108.7	-14.3%
2014	948.0	924.6	23.4	2.5%
2015	893.2	985.5	-92.4	-10.3%
2016	971.4	1050.5	-79.1	-8.1%
2017	1160.1	1119.7	40.5	3.5%
2018	1178.8	1193.4	-15.6	-1.3%
2019	1358.1	1320.0	38.0	2.8%

Obtained a posteriori difference ratio value of the model C=0.2017, small error probability value p=0.9, -a=0.0638, indicating that the model is more accurate and can be used for medium- and long-term forecasting.

3.1.2 Overhaul cost

Based on the maintenance history of Highway F, this paper selects 2034 as the year of overhauling. The cost of overhauling Highway F is $51,992,000 for the entire life cycle. The parameters are brought into the model equation (14) for the overhaul cost and the cost is discounted to 2023 to obtain the overhaul cost of $51,992,000 over the life cycle of Freeway F.

3.2. Life cycle management costs

Based on the audit reports of Highway F in the past years, statistics were obtained from 2010 to 2019 as shown in Table 5, and regression analysis was used to analyse the management costs and predict the management costs in the future years.

Table 5. Management Costs of Highway F from 2010 to 2019 (in millions of dollars)

Year	Management cost	Year	Management cost
2010	9428.5	2015	11703.5
2011	10849.4	2016	11203.6
2012	10885.6	2017	11605.8
2013	11172.0	2018	12453.5
2014	11143.9	2019	13528.9

The basic form of the linear model is $y = \alpha + \beta x$, where y is the management cost, x is the age of the road, α and β are the model parameters, and the fitting results are shown in Table 6.

Table 6. Model fitting results

Parameter	Value	t value	P value	R^2
α	2983.8	1.726	<0.05	0.8007
β	317.5	4.820	<0.01	

3.3 Life cycle environmental costs

3.3.1 Carbon costs incurred by the moving vehicles

Based on the IRI detection data of Highway F in previous years, this paper takes the average IRI value of 1.62 from 2015 to 2019 to calculate the cost of carbon emissions generated when the vehicle is traveling. The emission factors for gasoline and diesel are shown in Table 7, carbon emission factors are shown in table 8.

Table 7. 100-kilometer fuel consumption(L/100km)

Type	Passenger car	Truck
Type 1	8.843	13.154
Type 2	19.614	22.179
Type 3	23.115	22.737
Type 4	23.115	23.166
Type 5		26.219
Type 6		29.803

Table 8. Carbon mission factor of fuel

Type	Low-level heat generation (MJ/kg)	Carbon content per unit calorific value(g/MJ)	Carbon emission factor(kgCO2/kg)
Gasoline	44.8	18.9	3.10
Diesel	43.3	20.2	3.21

According to the "China Automotive Low Carbon Action Plan Research Report", the 100km carbon emissions of new energy vehicles is 15.7kg.

According to the market data of Guangzhou Carbon Emission Right Exchange, the average market price in January 2024 is 76 yuan/ton, according to which the carbon emission cost of each type of vehicle when driving is calculated as shown in Table 9.

Table 9. Cost of carbon emissions per kilometer of driving for each vehicle type(RMB/km)

Type	Passenger car	Truck
Type 1 (fuel car)	0.012	0.020
Type 1(new energy car)	0.009	
Type 2	0.030	0.034
Type 3	0.036	0.035
Type 4	0.036	0.036
Type 5		0.040
Type 6		0.046

The cost of carbon emissions of new energy vehicles is only three-quarters of the fuel car, although the smallest unit of measurement of 0.01 yuan on the charge does not reflect the gap, but it is certain that the vigorous development of new energy vehicles is the realization of China's energy saving and emission reduction.

3.3.2 Carbon emission cost from the maintenance phase

This paper collects the data of each maintenance project of F highway in recent years to form the data sample of this section, and carries out the regression analysis, the regression equation is shown in equation (24), and the fitting results are shown in Figure 1.

$$y = 0.0064x \tag{24}$$

Where y means the carbon emission cost, x is the cost of maintenance work.

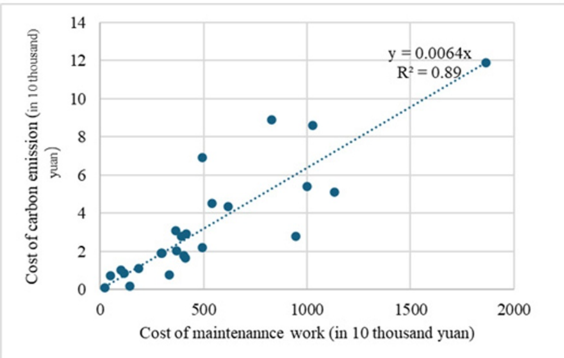

Figure 1. Fitting results for carbon emission costs and conservation engineering costs

From Figure 1, it can be seen that the carbon emission cost generated by maintenance works is about 0.0064 times of the cost of maintenance works, the R^2 of the regression result is 0.89, which indicates that the degree of fit is good, and the t-value of the model parameter is 13.937, with a p-value < 0.0001, which indicates that the model has a high prediction accuracy, and can be based on which to extrapolate the carbon emission cost generated by the maintenance phase of the road.

4. Conclusions

In this paper, highway maintenance and management costs are studied from the perspective of full life cycle cost analysis, and highway maintenance costs are divided into maintenance costs, management costs and environmental costs, and relevant prediction models and calculation models are established. Among them, the maintenance cost is predicted by GM(1, 1) model based on time series, and the management cost is analysed by regression analysis, and the prediction model with the traffic life as the independent variable is established. based on the carbon trading mechanism, the carbon emissions generated during the operation of highways are divided into those generated during the vehicle driving phase and those generated during the road maintenance phase, and emission factor method is used to predict the carbon emissions of highways. The results of the study show that the cost of carbon emissions generated by new energy vehicles during driving is only 3/4 of that of fuel vehicles, and more than 90% of the carbon emissions during highway operation are generated by driving vehicles.

However, the prediction of maintenance and management costs in this paper is only a time series prediction, and the relationship between maintenance and management costs and other influencing factors can be further studied in the light of the actual situation in order to obtain more accurate prediction results.

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