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Asphalt Pavement Long-Term Performance Prediction Based on Mechanistic-Empirical Methodology

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Abstract. The long-term performance trends of asphalt pavements are pivotal to the concerns of road maintenance authorities. However, predicting the longevity of asphalt pavement performance accurately is a complex challenge due to the multitude of factors influencing its deterioration. This paper constructs a predictive model for long-term behavior of asphalt pavements grounded in the mechanistic-empirical methodology. An extensive observation was conducted on highways, where data on the pavement condition index and the road quality index were meticulously gathered. Subsequently, the model's life factor and shape factor parameters were corrected. The findings indicate that the predictive methodology derived from mechanistic-empirical methodology for asphalt pavement performance exhibits commendable accuracy and good generalization capabilities.

Keywords: Asphalt Pavement; Mechanistic-Empirical Methodology; Long-Term Performance

1. Introduction

The long-term performance of asphalt pavements is primarily evaluated through the Pavement Condition Index (PCI) and the Road Quality Index (RQI). These indices are critical in guiding pavement maintenance decisions and provide essential data support for road maintenance management authorities to develop pavement maintenance plans and allocate maintenance funds effectively [1, 2]. Over time, the performance of pavements degrades due to a variety of factors, including traffic loads, rainfall, ultraviolet radiation, among others [4]. Consequently, forecasting the degradation trends of pavement performance has emerged as a crucial process in road management.

A plethora of research findings suggest that the approaches for forecasting the long-term performance of road surfaces are mainly categorized into three types: artificial intelligence (AI) prediction techniques, probabilistic prediction models, and mechanical empirical formulas [5]. Among these, AI prediction has gained prominence in recent years and encompasses methods such as grey system forecasting, backpropagation (BP) neural networks, and time series analyses. AI prediction models are typically characterized by their high levels of predictive precision. However, they often suffer from a lack of interpretability, effectively functioning as grey box systems, which complicates the analysis of how random variables influence road surface performance [6].

To tackle the challenge of limited interpretability in AI predictive models and to account for the inherent randomness in the evolution of road surface conditions, certain researchers have turned to probabilistic forecasting techniques. These methods aim to uncover the long-term trends in the performance of road surfaces, with prominent approaches including Markov Chains, Semi-Markov

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Chains, and Residual Curve predictions [7]. Nevertheless, because of the diverse levels of variability in the factors influencing road performance—such as traffic loads, environmental conditions, pavement composition, and maintenance practices—probabilistic prediction models face difficulties in guaranteeing the consistency and dependability of their forecasts.

To mitigate the issues of low reliability in probabilistic models and the lack of interpretability in AI models, certain studies have resorted to the mechanical empirical approach [8] for predicting the long-term performance of road surfaces. This method initializes its analysis with an understanding of the mechanics governing pavement structure, incorporating variables such as pavement thickness, modulus, and structural strength, to formulate a model depicting the deterioration of pavement physical attributes. Concurrently, it harnesses extensive observed data on road conditions over time to correlate pavement physical attributes with performance indicators. Nevertheless, the model's generalizability is notably hindered by the intricacy of computations, the extensive array of parameters, and the weak correlation between these parameters and performance outcomes.

This paper is grounded in the mechanical empirical approach, utilizing the mechanical empirical index equation as its foundational framework to develop models for the deterioration of asphalt pavement distress conditions and pavement ride quality. The study employs long-term pavement performance data, which is meticulously fitted and examined using extensive road condition observations accumulated over the years. These data are instrumental in refining the model coefficients. Ultimately, the predictive accuracy and versatility of the model are validated through its application on both highways and urban road networks.

2. 2. Methodology Section Headings

2.1 2.1 Asphalt pavement performance degradation patterns

The long-term performance degradation of asphalt pavements generally exhibits four forms: concave, S-shaped, convex, and linear, as shown in Figure 1 [9]. Concave curves in road performance data suggest that there is an initial rapid deterioration of the asphalt pavement soon after its construction, which then progressively slows down over time. This type of decline is particularly detrimental to the longevity of asphalt surfaces and is commonly associated with substandard road construction practices. Furthermore, it poses a significant challenge in implementing effective maintenance strategies to mitigate the decline in performance of asphalt pavements. The S-shaped curve is an ideal asphalt pavement deterioration curve. In the early stage of pavement use, the performance degradation is relatively slow. As the years go by, the speed of damage accelerates, but at the same time, due to the intervention and maintenance of maintenance measures, the rate of decline in pavement performance slows down. After the design life, without maintenance incentives, the pavement performance drops sharply, showing a concave trend, but the rate of decline in performance is much greater than that of the concave curve. A convex curve in the context of road pavement performance suggests that initially, the pavement demonstrates robust resistance to damage from vehicle loads and environmental influences, exhibiting a gradual rate of deterioration. However, as the road's service life extends and traffic volumes increase, the pavement begins to exhibit signs of distress such as cracking and deformation. Consequently, the rate of decline in pavement performance accelerates over time. Linear degradation curves for asphalt pavements are increasingly rare in contemporary construction. These curves illustrate a direct, proportional decline in the performance of asphalt surfaces once they are commissioned. Essentially, this model suggests that the pavement experiences accelerated wear early on, and subsequently, it may suffer from inadequate maintenance and rehabilitation as it approaches its later life cycle.

2.2 2.2 Pavement Condition Index Degradation Model

The basic decay model for of asphalt pavements is shown in Formula (1), which was first proposed by Professor Sun Lijun of Tongji University [10].

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$$PCI = PCI_0\{1-\exp[-(\frac{\alpha_p}{y})^{\beta_p}]\} \tag{1}$$

Where PCI is pavement condition index, PCI_0 represent initial pavement condition index, y refer to pavement service life, α_p donate the life factor of pavement condition index decay model and β_p donate the shape factor of pavement condition index decay model. The parameters for the pavement condition index decay equation are presented in Formulas (2) to (6).

$$\alpha_p = K_{r\alpha}K_{m\alpha}\lambda\{1-\exp[-(\frac{\eta}{l_0})^{\zeta}]\} \tag{2}$$

$$\lambda = a_1 h^{b1} ESAL^{c1} \tag{3}$$

$$\eta = a_2 h^{b2} ESAL^{c2} \tag{4}$$

$$\zeta = a_3 h^{b3} ESAL^{c3} \tag{5}$$

$$\beta_p = K_{r\beta}K_{m\beta}a_4 h^{b4} ESAL^{c4} l_0^d \tag{6}$$

Where $ESAL$ represents equivalent standard axle loads, h is Asphalt pavement layer thickness, l_0 donates initial deflection of asphalt pavement, $K_{r\alpha}$ and $K_{r\beta}$ refer to environmental impact coefficient.

$$K_{r\alpha} = (0.2868-0.0493W)\cdot(3.5297+0.0393T) \tag{7}$$

$$K_{r\beta} = (0.2992-0.0559W)\cdot(3.6373+0.0126T) \tag{8}$$

$$W = \frac{R}{Z} \tag{9}$$

Where $K_{m\alpha}$ and $K_{m\beta}$ refer to asphalt impact coefficient, T represents the average annual temperature, W is moisture coefficient, R donates annual precipitation, Z donates annual evaporation, a,b,c,d are regression coefficients of the prediction model.

In Formula (1), the model parameter (α_p,β_p) carries distinct physical implications. Specifically, parameter (α_p,β_p) is capable of establishing a unique correspondence with the road performance degradation curve. This indicates that varying combinations of α_p and β_p can accurately represent four distinct patterns of road performance degradation. When both α_p and β_p are greater than 0, the performance metrics of the asphalt pavement exhibit a consistent decline. As y tends towards zero, PPI converges to PPI_0, at which point the performance indicators of the asphalt pavement revert to their original levels. Conversely, as y tends towards infinity, PPI tends towards 0. Additionally, if y is equal to α_p, the performance degradation curve must necessarily intersect at the point $(\alpha_p, 0.632PPI_0)$, irrespective of the values of α_p and β_p. In the degradation curve of road surface performance, parameter α_p denotes the duration of road usage until the road's performance drops to 63.2% of its original state. Consequently, α_p is referred to as the life factor. The typical range for the value of α_p, based on the structural design life of asphalt pavements, falls between 3 and 15. When the value of α_p is constant, varying the magnitude of β_p alters the contour of the associated pavement performance degradation curve. Consequently, β_p is referred to as the decay shape parameter. Typically, its value spans from 0.2 to 2.

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2.3 2.3 Road Quality Index Degradation Model

The degradation model for the riding quality index of asphalt pavements maintains the same structure as Equation (1). However, the computations for the life factor and the decay shape factor differ from the original model.

$$RQI = RQI_0 \left\{ 1\text{-}\exp[-(\frac{\alpha_r}{y})^{\beta_r}] \right\} \tag{10}$$

Where RQI is road quality index, RQI_0 represent initial road quality index, y refer to pavement service life, α_r donate the life factor of road quality index decay model and β_r donate the shape factor of road quality index decay model.The parameters for the road quality index decay equation are presented in Formulas (11) and (12).

$$\alpha_r = a_1 h^{b1} ESAL^{c1} l_0^{d1} \tag{11}$$

$$\beta_r = a_2 h^{b2} ESAL^{c2} l_0^{d2} \tag{12}$$

Where $ESAL$ represents equivalent standard axle loads, h is Asphalt pavement layer thickness, l_0 donates initial deflection of asphalt pavement, a,b,c,d are regression coefficients of the prediction model.

3. 3. Results and discussion

3.1 3.1 Long-term Pavement Observation Experimental Conditions

This paper focuses on two expressway sections, S11 and G56, which have been monitored for 5 and 6 years, respectively. Both sections feature pavements constructed with Stone Matrix Asphalt (SMA), and the surface layer of these pavements has a uniform thickness of 18cm. The pavements experience an equivalent standard axle loads of roughly 11,000 times per day per lane, with a representative deflection value of approximately 0.2mm. The surface layer is composed of modified asphalt, with respective asphalt influence coefficients of 1.5 and 1.1. Located in an area with an average annual temperature of 16.9°C, these sections are subject to an average annual rainfall of 1,477mm, an average annual evaporation of 1,823mm, and an environmental impact coefficient of 0.978. The initial regression parameters for the pavement damage condition index and the pavement riding quality index model are presented in Table 1.

Table 1. Life factor and shape factor parameters of the prediction model

Parameters of PCI prediction model		Parameters of RQI prediction model	
Parameters	Value	Parameters	Value
λ	24.70158	a_1	30.066
η	42.12559	b_1	0.239
ζ	0.578832	c_1	-0.238
a_4	0.6536	d_1	-0.119
b_4	0.3349	a_2	0.504
c_4	-0.0255	b_2	0.15
d	-0.0981	c_2	-0.164
W	1.035	d_2	-0.05

3.2 3.2 Long-term Pavement Observation Data

The study focuses on two specific stretches of highway located in Zhejiang Province, where comprehensive long-term performance monitoring of asphalt pavements has been conducted. Data

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collection for each of these sections has been ongoing for over five years, encompassing key performance indicators such as the PCI and the RQI. The findings from these observations are detailed in Tables 2 and 3, which provide insights into the pavement conditions and road quality over time.

Table 2. Long-Term performance observation data of expressway (S11) pavement

Observation year	Duration (years)	PCI value	RQI value
2010	0	97.5	98.8
2011	1	95.4	97.9
2012	2	94.3	96.2
2013	3	92.51	93.77
2014	4	91.6	92.8

Table 3. Long-Term performance observation data of expressway (G56) pavement

Observation year	Duration (years)	PCI value	RQI value
2009	0	96.1	93.2
2010	1	95.1	92.1
2011	2	92	90.5
2012	3	91.5	92
2013	4	90.62	90.6
2014	5	89.59	88.9

3.3 3.3 Pavement Performance Predictions of Initial Model

The PCI and RQI for two monitored expressway segments were forecasted using preliminary models that hinged on the pavement distress condition index and the pavement riding quality index. These models projected data over a span of 8 years. The comparison between the actual observational data and the forecasted data is illustrated in Figures 1 through 4.

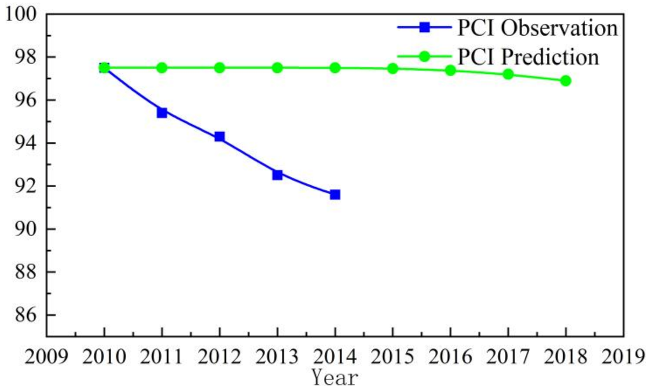

Fig.1 Observation and prediction PCI results of S11 expressway

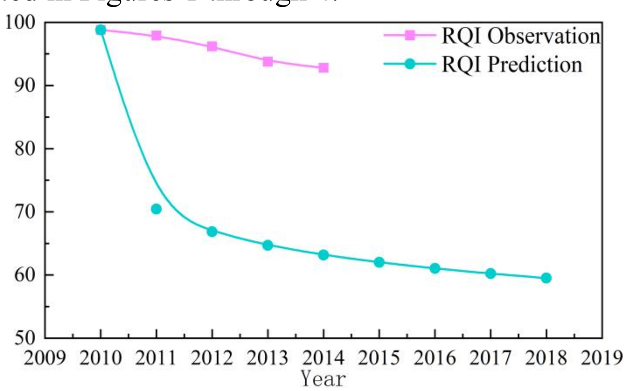

Fig.2 Observation and prediction RQI results of S11 expressway

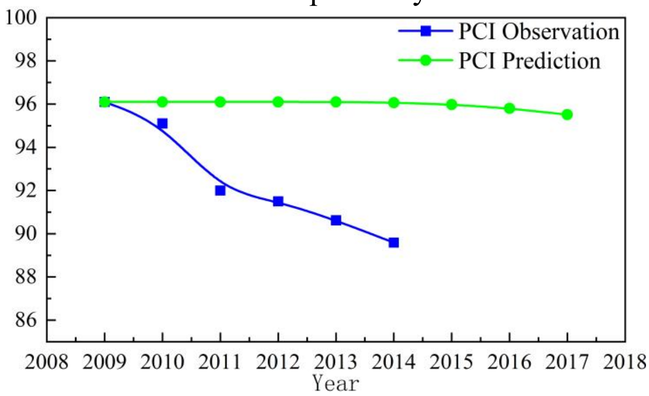

Fig.3 Observation and prediction PCI results of G56 expressway

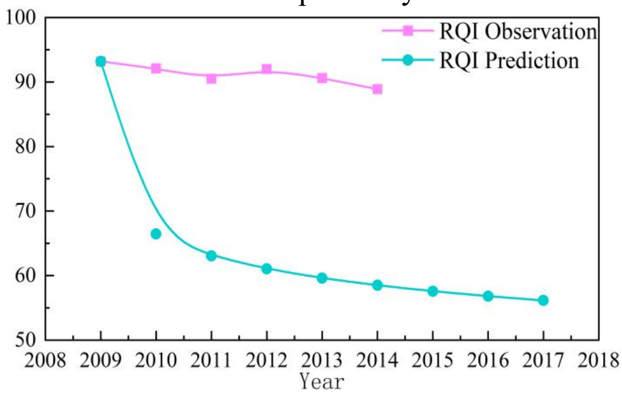

Fig.4 Observation and prediction RQI results of G56 expressway

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From Figures 1 to 4, it is evident that there is a notable discrepancy between the actual observational data and the predicted data. Furthermore, the prediction errors for both the pavement damage condition index and the pavement ride quality index exhibit an increasing trend over the years. The average prediction error for the S11 expressway's pavement damage condition index is 3.48, while for the pavement ride quality index, it stands at 24.3%. In the case of the G56 expressway, the average prediction error for the pavement damage condition index is 3.32%, and for the pavement ride quality index, it is 25.22%. Analyzing the trend of the prediction curves, the shape of the pavement damage condition index prediction aligns fairly well with the observational curve, with the primary source of error being the shape factor. Conversely, the pavement ride quality index prediction curve shows minimal shape discrepancy with the observational curve, with the prediction error primarily attributed to the life factor.

3.4 3.4 Model Parameters Corrected

Based on the preliminary prediction outcomes of the initial models for the PCI) and RQI, adjustments to the model's initial parameters are required. The shape factors within the models reveal coefficients b_4 and c_4 as the most sensitive, whereas coefficients a_1 and c_1 in the life factors exert the most significant influence. Consequently, the PCI model should focus on refining coefficients b_4 and c_4 of the shape factors, whereas the RQI model should concentrate on modifying coefficients a_1 and c_1 of the life factors. The detailed parameter adjustments are presented in Table 4.

Table 4. Correction of the lifespan factor and shape factor parameters in prediction model

Parameters of PCI prediction model			Parameters of RQI prediction model		
Parameters	Initial value	Corrected value	Parameters	Initial value	Corrected value
b_4	0.3349	0.3148	a_1	30.066	80.065
c_4	-0.0255	-0.115	c_1	-0.238	0.537

3.5 3.5 Pavement Performance Predictions of Corrected Model

The model was refined by utilizing the Pavement Condition Index (PCI) and the Riding Quality Index (RQI) to forecast the PCI and RQI values for the two inspected sections. The comparison between the actual observed data and the predicted outcomes is illustrated in Figures 5 through 8.

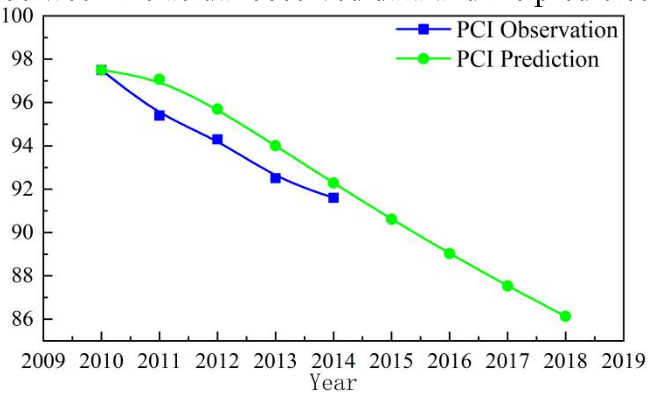

Fig.5 Rresults of S11 expressway

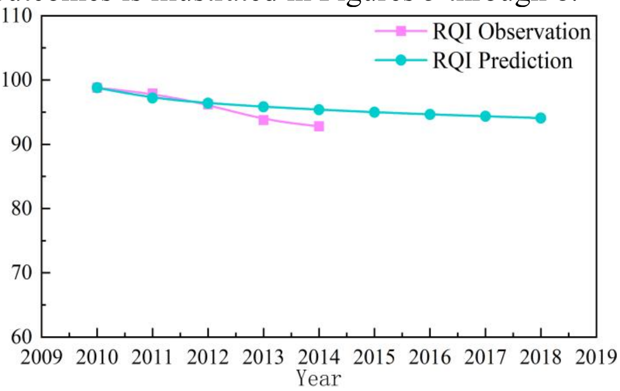

Fig.6 Observation and prediction RQI results of S11 expressway

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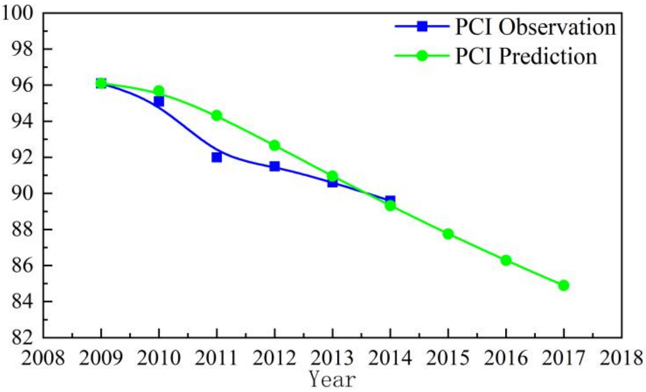

Fig.7 Observation and prediction PCI results of G56 expressway

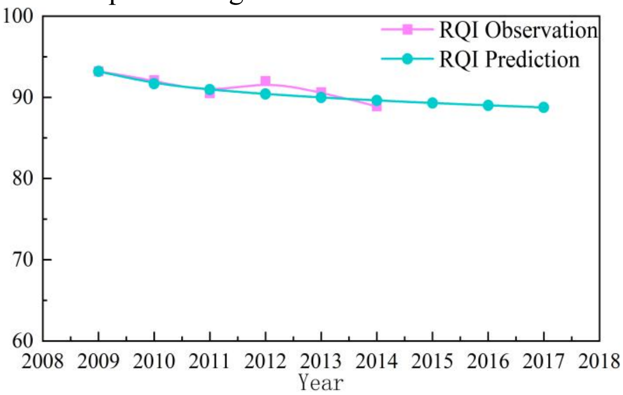

Fig.8 Observation and prediction RQI results of G56 expressway

Figures 5 to 8 clearly demonstrate a marked reduction in the discrepancy between the actual observed data and the predicted data. Moreover, the trends in the PCI and the RQI align closely. For the S11 highway, the average prediction error for the PCI is 1.12%, while for the RQI, it is 1.18%. On the G56 highway, the average prediction error for the PCI is 0.85%, and for the RQI, it is 0.69%. Following model refinement, the average prediction error for the PCI was reduced by 2.41%, and for the RQI, it was decreased by 23.82%. These model prediction outcomes suggest that the PCI and RQI can be reliably forecasted using the mechanical empirical model with a high degree of accuracy.

3.6 3.6 Analysis of Model Generalization Ability

Generalization capability is a crucial metric for assessing the effectiveness of predictive models. Utilizing extensive observational data of highway pavements, this study develops predictive models for the PCI and RQI. Following meticulous parameter tuning, these models exhibit robust predictive performance. To broaden the applicability of these models, two urban road segments, G235 and G330, which are subjected to similar climatic conditions, were selected for further analysis. The study collates PCI and RQI data from 2019 to 2023 for these routes and employs the developed predictive models to generate forecasts. The predictive outcomes are illustrated in Figures 9 to 12.

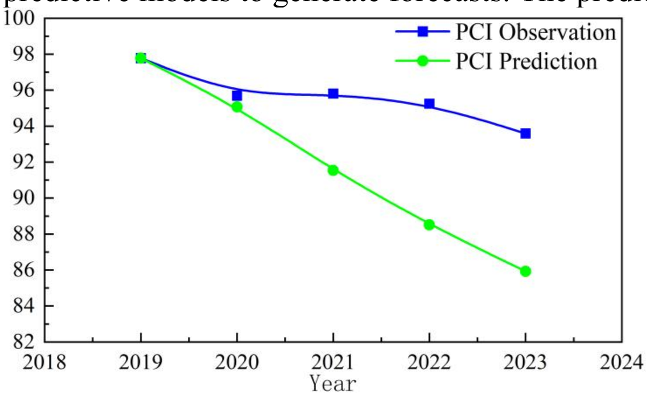

Fig.9 Observation and prediction PCI results of G235 urban roads

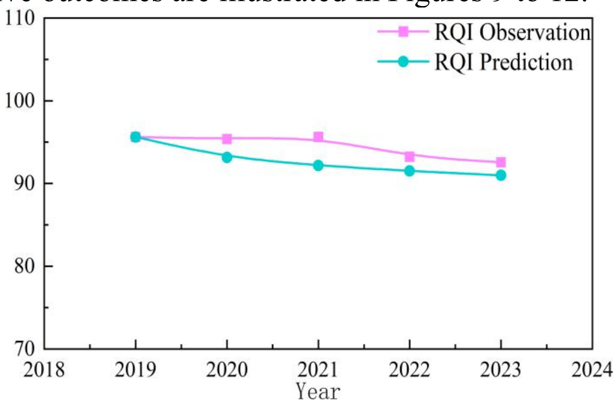

Fig.10 Observation and prediction RQI results of G235 urban roads

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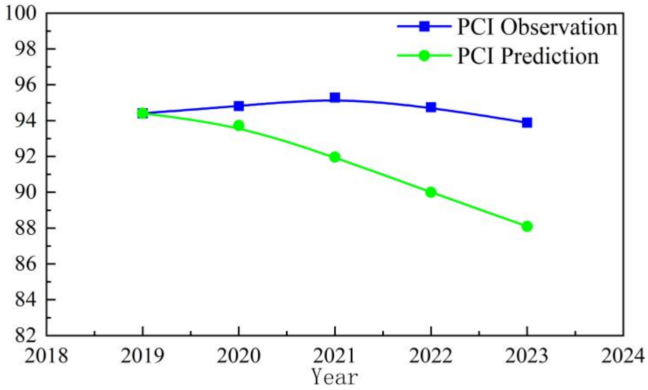

Fig.11 Observation and prediction PCI results of G330 urban roads

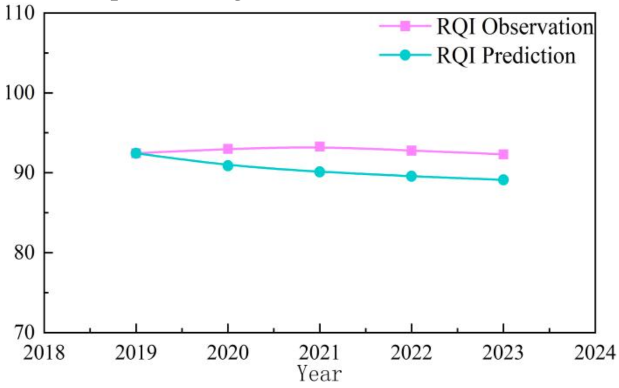

Fig.12 Observation and prediction RQI results of G330 urban roads

From Figures 9 to 12, it is evident that the PCI and RQI prediction models demonstrate varying degrees of generalization capabilities. The RQI model exhibits a higher level of generalizability, experiencing only a slight decline in prediction accuracy when applied to urban roads from highways. Specifically, the prediction error for the pavement ride quality index on G235 is 1.38%, and on G330 it is 2.52%, representing an increase of 0.44% and 1.58% over the highway predictions, respectively. In contrast, the PCI model exhibits a weaker generalization ability, with a notable rise in prediction error. For G235, the prediction error is 2.49%, and for G330, it is 3.16%, marking an increase of 1.5% and 2.17% compared to the highway predictions, respectively. Consequently, the RQI prediction model demonstrates superior generalization capabilities compared to the PCI prediction model.

4. Summary

In this research, we developed two long-term performance prediction models for road surfaces, grounded in mechanical expertise. These models utilized extensive observation data from highways to conduct predictive experiments on the PCI and RQI. Following the prediction outcomes, the models were appropriately parameterized. Subsequently, we applied these models to forecast the long-term performance of urban road surfaces, evaluating their generalizability. Based on the experimental results, the paper yields the following conclusions:

- The prediction models for the PCI and RQI have high accuracy in predicting the long-term performance of highways, with prediction errors less than 5%.
- The generalization ability of the prediction models is insufficient, as the prediction error significantly increases when the models are applied from highways to urban roads.
- The experimental results show that the generalization ability of the PCI prediction model is lower than that of the RQI prediction model.

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