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Decision Model of Pavement Maintenance Based on International Roughness Index

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Abstract

When choosing the pavement maintenance scheme, the actual pavement condition cannot be truthfully reflected by traditional fixed indexes and weights, making accurately evaluating the pavement condition particularly important. This study aims to analyze the relationship between international roughness index (IRI) and pavement condition index (PCI), and propose the IRI-based pavement condition rating to improve the correctness of the maintenance decision. Based on the inspection data and maintenance data of large and medium-sized repair and maintenance projects in Shaanxi Province, representative road sections in northern Shaanxi, The Central Shaanxi Plain, and southern Shaanxi were selected to establish a simple model to examine the relationship between PCI and IRI. The model development data were selected from 312 different road sections, including 1665 data points. The model validation data were selected from 140 road sections, including 333 data points. The road sections selected for validation data and those for development data had the same data range. Results demonstrate that, the S-function could best express the relationship between PCI and IRI. The function established by data fitting had a high coefficient of determination (R^2=0.959), and the deviation of the predicted IRI value was low. The model validation of different datasets all yielded relatively more accurate predictions (R^2=0.973). Finally, the IRI-based pavement condition rating was proposed, and the pavement condition was divided into five grades, namely, excellent, good, fair, poor, and very poor, by using IRI detection data. This proposed rating provides double verification of the pavement condition with PCI rating and improves the correctness of the maintenance decision.

Keywords: Asphalt pavement, International roughness index, Pavement condition index, Pavement maintenance

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1. Introduction

With the rapid economic development, the highway network is increasingly completed, the mileage, operation time, and traffic volume are increasing, and the pavement of each highway is damaged to varying degrees, accompanied by the gradual decline of pavement performance. Hence, maintaining the good condition of highways by implementing maintenance projects is necessary. At present, the implementation of maintenance projects has considerably increased and now it has entered a large-scale maintenance stage. Reliable pavement maintenance decision and accurate pavement performance evaluation play a vital role in improving the quality of pavement maintenance [1].

Maintenance engineering is the main way to improve and enhance the quality of highway conditions [2]. At present, the main index of highway pavement maintenance decision is pavement condition index (PCI) [3], which can be obtained by observing surface damage and statistically analyzing pavement samples and can comprehensively evaluate pavement condition [4]. In addition, PCI reveals the structural integrity of the pavement and the damage state of the pavement surface. For fixed highway pavement maintenance, the pavement damage rate value that affects PCI is related to many factors, such as alligator cracking, cracks, potholes, looseness, subsidence, rutting, waves, and upheaval [5]. The value of each factor is obtained from manual detection and automatic detection, and subjective human factors have great influences. The results obtained under the fixed weights corresponding to different factors are dissimilar from the actual highway conditions. In the service process of highways, interregional differences are large, the actual condition of each road cannot be accurately embodied by the nationwide unified highway condition evaluation standard, and evaluating pavement performance by obtaining a comprehensive evaluation index through simple weighting of subindexes is not objective because this disagrees with the discriminant model of each performance index. The data needed by PCI are collected by visual inspection or image-based investigation. Visual inspection takes a long time and leads to traffic interruption, the actual operation is difficult for long roads and large-scale road networks, and conducting surveying work on roads for a long time is relatively dangerous for inspection workers. Image-based measurement methods, for example, collecting pictures, videos, or digital images using vehicles, are faster and safer but require costly advanced equipment.

One of the main parameters affecting the driving quality is pavement roughness [6]. Pavement roughness increases fuel consumption and greenhouse gas emissions, reduces vehicle driving efficiency, and may lead to traffic safety problems. International roughness index (IRI) is an internationally shared pavement roughness measurement index, which meets the requirements for time stability, transferability, and easy measurement [7]. Pavement roughness can be quantified by IRI. IRI is the ratio of the cumulative vertical displacement of the vehicle body

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suspension system to the driving distance within a certain driving distance when a 1/4 wheel (that is, a single wheel, similar to a trailer) runs on the road at 80 km/h. IRI, which takes a 1/4 vehicle model as a dynamic calculation scheme, not only has the advantages of dynamic systems but also avoids the shortcomings of actual dynamic measurement systems whose characteristics vary with time. This index can be nearly convertible or compatible with the measurement indexes of all roughness detectors [8].

Compared with IRI, the pavement condition investigation required to determine PCI is time consuming and costly. If the relationship between IRI and PCI can be established, the PCI value can be determined through IRI, which can not only reduce capital consumption but also provide a reference basis for highway conditions.

2. State of the art

The accurate evaluation of pavement conditions exerts an important influence on the highway maintenance decision, so this has been extensively investigated by many scholars. L. K. Li et al. screened road sections with poor conditions according to the boundary conditions of the overall PCI, thus effectively reducing the capital needs of the whole road network maintenance engineering [9]. W. D. Wu et al. established a pavement performance prediction model based on theory of least square support vector machine, which improved the intelligent informatization level of highway maintenance [10]. L. Li et al. enhanced the pertinence of maintenance countermeasure selection by combining neural networks and the traditional decision tree optimization-based pavement decision [11]. L. Chen et al. established three critical points from pavement performance prediction, maintenance standard setting, and the maintenance decision model based on fracture percent and crack pouring rate, and then proposed an analysis method can be used to improve maintenance demand [12]. W. Zhou et al. stated the factors influencing the decision process were not unique, which should be increased or reduced according to the actual situation [13]. J. M. Pinat et al. proved the objective and subjective evaluation results of PCI were similar, where subjective evaluation could serve as a simple pavement evaluation method for unplanned cities [14]. P. Xu et al. believed intelligent detection was also applicable to whole-process and whole-space-time disease monitoring of pavements and could further facilitate the fully automatic efficient analysis of fields such as road service performance and road maintenance strategy optimization [15]. M. Jin et al. established a prediction model using the evaluation indexes of asphalt pavement performance and verified the model accuracy was high [16].

At present, most of the decision models of pavement maintenance schemes are based on PCI or IRI. PCI and IRI are the basic indexes of highway maintenance decision and can reflect the pavement quality. A. Ali et al. analyzed the factors of pavement performance in regions with awful weather and found PCI is most highly correlated with the damage degree of highways [17]. I. Kravcovas et al. established a new pavement performance model to analyze the pavement maintenance and repair of urban roads effectively [18]. J. Meegoda et al. constructed a pavement performance prediction model based on IRI and effectively treated pavements under different pavement conditions [19]. S. Bao et al. found a multi-objective optimization model can effectively solve the actual pavement maintenance decision problem [20]. N. Radovi et al. evaluated the condition of road networks using IRI [21].

Based on the above research literature, pavement condition evaluation is one of the important factors of highway maintenance decision, PCI and IRI are the indexes for evaluating pavement conditions and are the basic indexes for establishing a pavement maintenance decision model. The pavement maintenance decision model based on PCI has a long-term fixed pavement condition quantification index [22], and the PCI value obtained under fixed weights cannot effectively analyze the actual pavement condition. Although IRI is capable of the pertinent evaluation of pavement conditions [23], no fixed IRI value analyzes the quality of pavement conditions to determine the highway maintenance scheme. PCI and IRI are indexes of pavement conditions, and some studies have found a correlation between them [24]. In this study, IRI was assumed to be correlated with PCI, so the relationship between IRI and PCI was established. The value of IRI corresponding to different pavement damage degrees was determined according to the rating of pavement conditions based on PCI, and an appropriate pavement maintenance scheme was chosen. Taking the pavement condition in Shaanxi Province, China, for example, the highway pavement conditions in different regions were investigated and detected, and the relationship between PCI and IRI was studied, providing a new reference for determining the value of PCI, determining the actual pavement condition, selecting the optimal maintenance and repair scheme, and providing a reference for reasonably determining the pavement maintenance scheme.

The organizational layout of this study was as follows. In Section 3, the selected regional topography, data points of pavement conditions, and the calculation method of pavement indexes were introduced. In Section 4, a data model was established using the selected PCI and IRI data, the goodness of fit was calculated, and reasonable function parameters were chosen. In Section 5, the established model was validated by selecting pavement data from regions environmentally consistent with the modeling region, and an appropriate maintenance scheme was chosen using IRI based on the model. In Section 6, according to the previous analysis, the conclusions were drawn.

3. Methodology

Shaanxi Province is located in the central and western parts of China, with an overall strip shape, a total geographical area of 205000 square kilometers, and a large north-to-south span of 900 kilometers. The north part is dominated by Loess Plateau, the population is mainly distributed in the central and southern parts, especially the Central Shaanxi Plain is most densely populated, and the interregional geographical environment is significantly different within the province. According to the regional characteristics of Shaanxi, the road data of Yulin, Weinan, and Ankang were selected as a basis for studying the pavement conditions in Shaanxi Province.

In this study, the detection data of evaluation indexes for major and medium maintenance of national and provincial trunk lines in Shaanxi Province in 2018–2022 were mainly used, including the roads differing in pavement structure and performance, road age, and traffic conditions in Yulin, Weinan, and Ankang in Shaanxi Province in five years. The data included the information of pavement conditions, such as alligator cracking, cracks, rutting, potholes, subsidence, pavement roughness, pavement ride quality, and pavement skid resistance, as shown in Table 1.

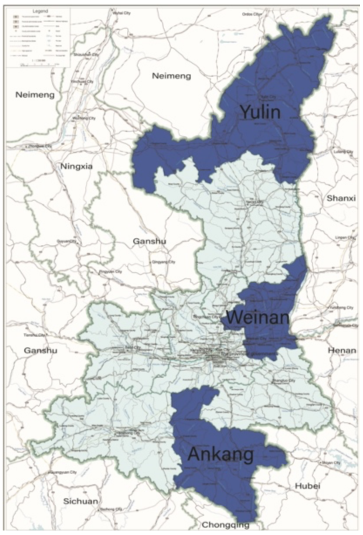

Fig. 1. Road network map of Shaanxi Province

Pavement damage was evaluated and calculated using PCI:

$$PCI = 100 - \alpha_0 DR^{\alpha_1} \tag{1}$$

$$DR = 100 \times \frac{\sum_{i=1}^{i_0} w_i A_i}{A} \tag{2}$$

where DR is the pavement distress ratio (%); α_0 is 15.00 for asphalt pavements; α_1 is 0.412 for asphalt pavements; A_i is the cumulative area of pavement damage of Class i (m^2); A is the pavement detection or investigation area (m^2); w_i is the weight or conversion coefficient for the pavement damage of Class i ; i represents the type of pavement damage, including the damage degree (mild, moderate, and severe); i_0 is the total number of damage types including the damage degree (mild, moderate, and severe), taken as 21 for asphalt pavements.

Table 1. Model Development of a data point of a pavement damage survey form

Route name :S308	**Direction of investigation:Ankang's second-level highway**									**Inspector:**				
investigate subject	**degree**	**weights Wi**	**unit**	**Starting point pile number:**			**K15+000**		**Final Pile Number:**			**K16+000**		**Grand total**
				Section length:			**1000**		**Pavement width:**			**10**		
				1	2	3	4	5	6	7	8	9	10	
alligator cracking	mild	0.6	m^2											0
	moderate	0.8												0
	severe	1.0												0
block crack	mild	0.6	m^2	140	140	115	80	68	186	40	60	120	40	593
	severe	0.8								121		240	68	343
vertical crack	mild	0.6	m^2											0
	severe	1.0						15						3
horizontal crack	mild	0.6	m^2											0
	severe	1.0		4	7								18	5.8
potholes	mild	0.8	m^2			2		12			0.4			11.5
	severe	1.0												0
looseness	mild	0.6	m^2											0
	severe	1.0												0
subsidence	mild	0.6	m^2						86					51.6
	severe	1.0												0
rutting	mild	0.6	m											0
	severe	1.0												0
upheaval	mild	0.6	m^2											0
	severe	1.0												0
bleeding		0.2	m^2											0
patching		0.1	m^2	223										22.3

In accordance with the evaluation standard for asphalt pavement damage conditions specified in Highway Performance Assessment Standards (JTG 5210-2018), the pavement quality could be divided into five levels—excellent, good, fair, poor, and very poor—according to the damage condition, and the value range of PCI and corresponding subindexes was 0–100, as shown in Table 2.

Table 2. Asphalt pavement damage condition evaluation standard table

Evaluation level	**excellent**	**good**	**fair**	**poor**	**very poor**
PCI	≥90	≥80, <90	≥70, <80	≥60, <70	<60

IRI was tested according to the Specifications of Automated Pavement Condition Survey (JTG-T E61-2014).

4. Establishment of the data model

A total of 312 different road sections were randomly selected from Yulin, Weinan, and Ankang, including 1665 data points, to establish the data model. The data are listed in Table 1. After the PCI of all data points was calculated, the calculated value and the IRI values corresponding to all data points were plotted, as shown in Figure 2. The trend shown by the IRI–PCI curve was similar to the S-shaped curve of the sigmoid function in Equation (3) [25]. This S-function has been widely applied to pavements. In the field of pavement materials, the sigmoid function is often applied in the principal curve of dynamic modulus of asphalt mixture [26-28] and in pavement performance modeling and improvement research [29-30].

$$IRI = \frac{A}{B + \exp(C \times PCI)} \tag{3}$$

where *IRI* is the predicted international roughness index (m/km); *PCI* is the pavement condition index; *A*, *B*, and *C* are model function parameters.

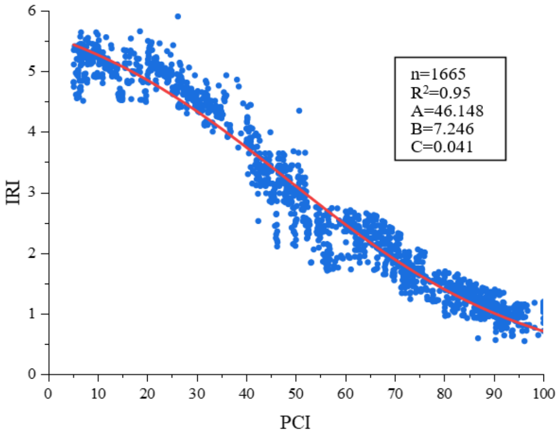

Fig. 2. The relationship between IRI and PCI values

The regression parameters of the S-function were determined by using nonlinear optimization in Excel to minimize the sum of square errors between the predicted IRI and the actual IRI, thus determining the model. To evaluate the accuracy of this relationship, the goodness of fit was calculated [31], as shown in Equations (4)–(8).

$$TSS = \sum_{i=1}^{n} (IRI_m - IRI_a)^2 \tag{4}$$

$$RSS = \sum_{i=1}^{n} (IRI_m - IRI_p)^2 \tag{5}$$

$$ESS = \sum_{i=1}^{n} (IRI_p - IRI_a)^2 \tag{6}$$

$$R^2 = 1 - \frac{RSS}{TSS} \tag{7}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(IRI_m - IRI_p)^2}{n}} \tag{8}$$

In Equation (4), *TSS* (total sum of squares) is the sum of squares of total deviations. In Equation (5), *RSS* (residual sum of squares) is the sum of squares of residuals. In Equation (6), *ESS* (explained sum of squares) is the sum of regression squares. In in Equation (4), R^2 is the coefficient of determination. In Equation (8), *RMSE* (root mean squared error) is the root mean square error.

In Equations (4)–(8), *n* is the number of total data points, IRI_m is the actually measured international roughness index, IRI_a is the average international roughness index, and IRI_p is the predicted international roughness index.

In this model, *TSS* represents the variance of the actually measured international roughness index, and *RSS* represents the sum of squares of the error-induced deviations between the actual IRI value and the predicted IRI value. R^2 is in the range of 0–1; the higher the coefficient is the better the goodness of fit. *RMSE* is a common measure of the difference between the predicted value of the model and the actual measured value. The lower the *RMSE* value is the better the fitting. Finally, according to the selected 1665 data points, the values of *A*, *B*, and *C* in the S-function (Equation 3) were taken as 46.148, 7.246, and 0.041, respectively, and the S-function is expressed by Equation (9).

$$IRI_p = \frac{46.148}{7.246 + \exp(0.041 \times PCI)} \tag{9}$$

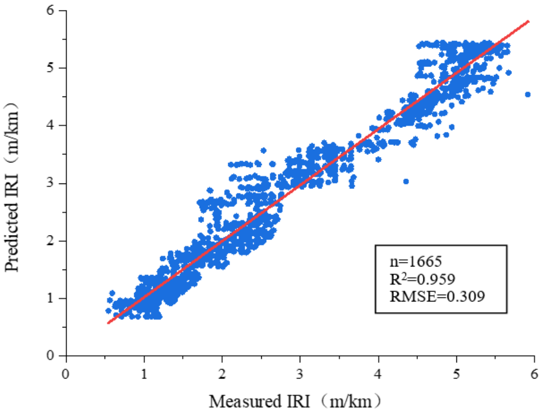

Fig. 3. Established relationship between model-measured IRI and predicted IRI

The relationship between the predicted IRI using the S-function and the actually measured IRI is depicted in Figure 3. The model produced an accurate prediction with a high R^2 (0.959) and a low *RMSE* (0.0309 m/km). The residual error and its normal distribution confirmed the normality and homoscedasticity of the function. In addition, the average error was 0.033, and the standard deviation was 0.308. Figures 3 and 4 show the deviation between the predicted IRI value and the measured IRI value was small.

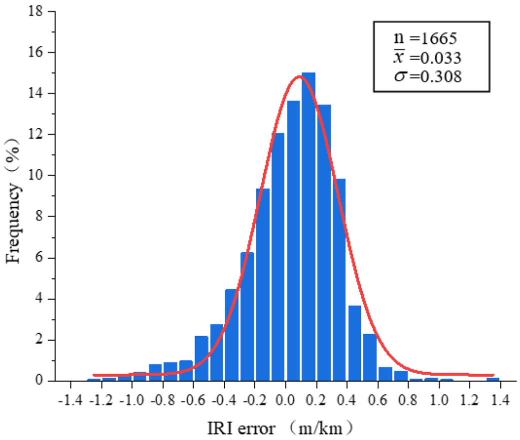

Fig. 4. Error distribution

5. Validation of the test model and formulation of the maintenance scheme

5.1 Validation of the data model

A total of 140 road sections were randomly selected in Yulin, Weinan, and Ankang, including 333 data points, which were used to validate the accuracy of the data model, as shown in Table 3. The validation data and modeling data came from national and provincial trunk lines in Shaanxi Province and had the same range.

The relationship between the IRI value predicted by the model and the IRI value measured is shown in Figure 5. A total of 333 data points were selected for the model validation. It could be clearly seen from the figure that the difference between the IRI calculated by the established model and the IRI actually measured was small, with the maximum difference of 0.637 and the minimum difference of 0.00041. Data point analysis revealed the correlation coefficient of this model was R^2=0.973, indicating good prediction accuracy.

Table 3. Pavement damage investigation for model validation at a data point

Route name :S308	**Direction of investigation:Yulin's second-level highway**									**Inspector:**				
investigate subject	**degree**	**weights Wi**	**unit**	**Starting point pile number:**			**K15+000**		**Final Pile Number:**			**K16+000**		**Grand total**
				Section length:			**1000**		**Pavement width:**			**10**		
				1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
alligator cracking	mild	0.6	m^2											0
	moderate	0.8												0
	severe	1.0												0
block crack	mild	0.6	m^2	20	120	105	86							199
	severe	0.8		46			210	226	456	386	375	451	365	2012
vertical crack	mild	0.6	m^2											0
	severe	1.0												0
horizontal crack	mild	0.6	m^2											0
	severe	1.0												0
potholes	mild	0.8	m^2							8	12			16
	severe	1.0												0
looseness	mild	0.6	m^2											0
	severe	1.0												0
subsidence	mild	0.6	m^2							60	75	20	77	139
	severe	1.0												0
rutting	mild	0.6	m											0
	severe	1.0												0
upheaval	mild	0.6	m^2											0
	severe	1.0												0
bleeding		0.2	m^2											0
patching		0.1	m^2											0

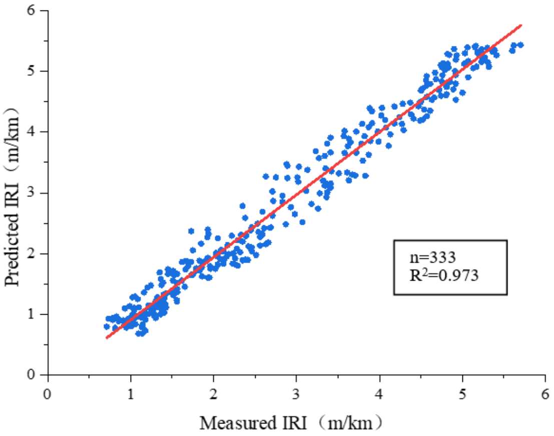

Fig. 5. Relationship between measured IRI and predicted IRI through model validation

5.2 Formulation of the maintenance scheme

According to Equation (9), the IRI range corresponding to the PCI range of the pavement condition level could be determined. Figure 6 shows the grade range of the pavement condition predicted by the IRI value, and the values reflected the relationship between IRI and the corresponding PCI under different pavement conditions. Through the function model given by Equation (9), IRI could be used as another verification standard for pavement conditions. According to the established model, the pavement quality could be classified based on the IRI value, which provided a new reference for selecting pavement maintenance projects and new data support for highway maintenance schemes.

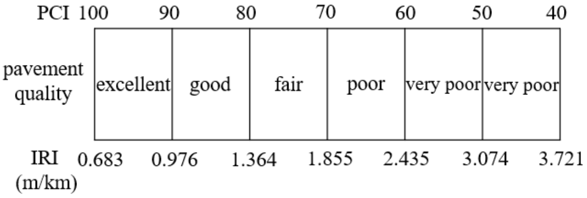

Fig. 6. IRI value corresponding to the given PCI value

Choosing a reasonable maintenance strategy according to the actual pavement conditions for the effective management of highway pavements is very important. The decision on maintenance strategies is influenced by the type and severity of pavement surface damage as well as the structure and flatness of the pavement. China's highway maintenance projects are divided into routine maintenance, minor repair, medium repair, overhaul, and reconstruction. According to the pavement quality classified by IRI, the highway maintenance project can be preliminarily selected, as shown in Table 4. According to the established data model, when the PCI value is greater than or equal to 90, the corresponding IRI value should be less than or equal to 0.98, and the pavement maintenance can be selected; when the PCI value is 80–90, the corresponding IRI value is 0.98–1.38, and minor repairs are preferred; when the PCI value is 70–80, the corresponding IRI value is 1.38–1.88, and medium repairs are chosen; when the PCI value is 60–70, the corresponding IRI value is 1.88–2.48, and overhaul is preferred; when the PCI value is less than 60, the corresponding IRI value is greater than 2.48, and reconstruction is selected.

Table 4. Maintenance schemes corresponding to the IRI value established by the model

Index	**Value**	**Index**	**Value**	Suggested maintenance schemes
PCI	≥90	IRI	≤0.98	Routine maintenance: remove dirt and sundries from the pavement; keep the pavement clean and tidy; eliminate water, snow, ice, and sand accumulation on the pavement; spread antiskid materials, dust suppressants or compact snow to maintain traffic; deal with diseases such as bleeding, upheaval, cracks, and looseness of the asphalt pavement; and repair and whitewash curbs.
	80–90		0.98–1.38	Minor repairs: repair potholes and subsidence on the pavement, and deal with diseases such as waves, local alligator cracks, and edge failure.
	70–80		1.38–1.88	Medium repairs: deal with serious pavement diseases
	60–70		1.88–2.48	Overhaul: Pavement patching, re-pavement or pavement widening and simple road pavement
	<60		>2.48	Reconstruction: resurface the whole pavement

6. Conclusion

In this study, the focus was on the relationship between IRI and PCI, and secondary asphalt highways in Yulin, Weinan, and Ankang of Shaanxi Province were chosen for analysis, including 312 pavement condition test points (1665 data points) for model development and 140 pavement condition test points (333 data points) for model validation. Finally, the following conclusions could be drawn:

(1) IRI and PCI have an S-shaped relationship. The prediction result of the proposed S-shaped model is accurate, and R^2 is 0.959. The validation shows the developed model can accurately predict IRI based on PCI data.

(2) Accurate predictions are produced by the dataset model validation of road sections from northern Shaanxi, the Central Shaanxi Plain, and southern Shaanxi. The correlation coefficient (R^2) of the function is 0.973, the IRI value calculated by the model established differs slightly from the actually measured value, and the prediction accuracy is high.

(3) The developed model can be used to predict the IRI value corresponding to the pavement condition rating. Based on the detection data of IRI, the pavement condition is divided into five grades, namely, excellent, good, fair, poor, and very poor, and this rating is capable double validation of the pavement condition with the PCI rating to improve the correctness of the maintenance decision.

The pavement condition rating proposed in this study based on IRI can help pavement maintenance workers choose the maintenance decision conforming to the pavement condition. However, this model, which is only used to study the pavement condition in Shaanxi Province, is not applicable to the data analysis of other regions. In follow-up study, the data range should be expanded, including different types of highways in different regions, to validate the universality and reliability of the model.

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