

Prediction method of highway pavement rutting based on the grey theory

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Abstract: In order to make a scientific pavement maintenance decision, a grey-theory-based prediction methodological framework is proposed to predict pavement performance. Based on the field pavement rutting data, analysis of variance (ANOVA) was first used to study the influence of different factors on pavement rutting. Cluster analysis was then employed to investigate the rutting development trend. Based on the clustering results, the grey theory was applied to build pavement rutting models for each cluster, which can effectively reduce the complexity of the predictive model. The results show that axial load and asphalt binder type play important roles in rutting development. The prediction model is capable of capturing the uncertainty in the pavement performance prediction process and can meet the requirements of highway pavement maintenance, and, therefore, has a wide application prospects.

Key words: prediction method; grey theory; cluster analysis; analysis of variance; pavement rutting

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Pavement performance prediction models are important tools for management systems at both network and project levels because they are essential for designing and planning maintenance and rehabilitation activities, as well as for the estimation of the necessary budget.

Most deterministic models are based on establishing regression relationships between relevant performance dependent indicators and independent variables, such as experienced traffic loadings, material characteristics, and environmental conditions^[1-3]. In particular, pavement performance quantifications involve complex mechanisms, some of which are unclear to users. It is, therefore, difficult to use regression techniques to determine these relationships quantitatively^[4-6].

The grey model is suitable for the scenario of limited data and is more competitive in short-term span^[7]. Pavement

performance prediction can be deemed as a grey system where many parameters do not have analytical solutions and suffer from various limitations when using traditional statistical analysis^[8]. To overcome the shortcomings of the existing models, this paper intends to develop a methodological framework based on the grey theory to predict pavement performance at the project level for highways.

1 Methodology

The existing pavement performance data on Chinese highways typically has the limited data and is unreliable. The small sample size makes the traditional statistical analysis approach designed for the large sample size unfeasible, and, meanwhile, the unreliability cripples the accuracy of the deterministic prediction models^[5]. Therefore, this paper develops a new method for establishing a pavement performance prediction model, combining the grey theory and cluster analysis. Fig. 1 shows the proposed methodological framework of pavement performance models. The methodology consists of three major modules: data analysis, model development and results analysis.

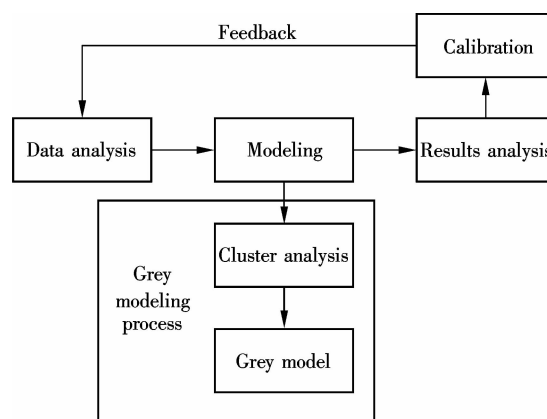


Fig. 1 Methodological framework

2 Case Study

Due to the traffic and environment, distresses of various types and severity levels, such as rutting, occur on asphalt pavements. Rutting may affect pavement riding quality and safety, especially on rainy days. Thus the study collected pavement rutting as the data sample to establish a grey model of pavement performance for Jiangsu

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Province's highways at a project level.

In Jiangsu province, a vehicle mounted laser profiler has been used to measure pavement rutting every year since 2003. The data of pavement rutting depth (RD) was collected every 10 m to evaluate pavement rutting conditions^[9]. The data used to establish the grey model consists of the following variables:

Traffic level: low (< 1 000 AADTT (average annual daily truck traffic)), medium ($\geq 1\ 000$ and $\leq 4\ 000$

AADTT), high (> 4 000 AADTT).

Asphalt type: modified asphalt (MA) and base asphalt (OA).

Mix type: stone mastic asphalt concrete SMA-13; dense graded asphalt concrete AK-13, AC-20 and AC-25; Superpave 20 (SUP-20) and Superpave 25 (SUP-25)

The data collected from four highways are analyzed in this paper. The descriptive information about four highways is summarized in Tab. 1.

Tab. 1 Descriptive information about four highways

Highway	Pavement section number	Service life/month	Asphalt mixture of surface layer	Asphalt mixture of middle layer	Asphalt mixture of bottom layer	Traffic level
Yanjing Highway	1	152	AK-13 with MA	SUP-20 with OA	AC-25 with OA	Medium
	2	152	AK-13 with MA	AC-20 with OA	AC-25 with OA	
	3	152	SMA-13 with MA	AC-20 with OA	AC-25 with OA	
Ninghang Highway	4	130	AK-13 with MA	AC-20 with MA	AC-25 with OA	High
	5	130	SMA-13 with MA	AC-20 with MA	AC-25 with OA	
Yanjiang Highway	6	104	AK-13 with MA	AC-20 with MA	AC-25 with MA	High
	7	104	SMA-13 with MA	AC-20 with MA	AC-25 with MA	
Yanhai Highway	8	92	SMA-13 with MA	SUP-20 with MA	SUP-25 with OA	Low
	9	92	SMA-13 with MA	AC-20 with MA	AC-25 with OA	
	10	92	AK-13 with MA	SUP-20 with MA	SUP-25 with OA	
	11	92	AK-13 with MA	AC-20 with MA	AC-25 with OA	

2.1 Data analysis

Statistical analysis is performed to reveal the relationship between pavement rutting and influence factors. The influence factors considered in this paper include traffic, asphalt type, and the aggregate grade type for different surface layers.

Analysis of variance (ANOVA) is used to inspect the correlations between rutting and the influence factors for each highway and traffic level group. Also, it is used to determine whether the asphalt binder type and mix type have any impact on the RD values^[2]. The null hypothesis of the ANOVA statistical test is that all the mean values of the two asphalt types and different mix types of three layers are the same (i. e., $\mu_{MA} = \mu_{OA}$, $\mu_{SMA-13} = \mu_{AK-13}$, $\mu_{AC-20} = \mu_{SUP-20}$, $\mu_{AC-25} = \mu_{SUP-25}$); otherwise, the alternative hypothesis is that at least one differs from the others^[10].

The ANOVA results of eleven cases obtained from the combination of highway and traffic levels are shown in Tab. 2. Four tests are performed for each combination^[2,5-6], which are the aggregate grade type of the surface layer, the aggregate grade type of the middle layer, the aggregate grade type of the bottom layer and all the modified asphalt pavement vs. all the ordinary asphalt

pavement values.

Based on the ANOVA results, the following conclusions are obtained:

1) There is significant difference between modified asphalt and ordinary asphalt, especially for pavements at low traffic level. However, the difference reduces gradually with increasing service time and an equivalent cumulative axle.

2) Significant differences are observed between different aggregate grade types of the surface layer except for the highways at low traffic volume, but the impact of mix type on pavement rutting varies for different pavement sections. The pavements with SMA-13 have better rutting resistance than those with AK-13. No significant differences are observed between different aggregate grade types of the middle layer.

3) For the bottom layer, there is no significant difference between aggregate grade types at the low traffic level, which is contrary for scenarios of medium and high traffic levels. Also, the pavements with SUP-25 have better rutting resistance than those with AC-25.

2.2 Cluster analysis

It is difficult to take all the influence factors into consideration when establishing the prediction model. The K-means clustering algorithm, a classical clustering algorithm based on centroid, is used to group the pavement sections and identify clusters with similar rutting deterioration process in order to avoid omitting redundant factors in this paper.

Rutting data from 2003 to 2011 was collected from the

Tab. 2 ANOVA results

Traffic level	Asphalt type	Mix type		
		Surface layer	Middle layer	Bottom layer
Low	MA	All	All	All
Medium	MA	SMA-13	All	SUP-25
High	MA	SMA-13	All	SUP-25

Yanjing highway as the analysis sample. The sample included 5 399 data points in north bound direction and 4 118 data points in south bound direction. Rutting data

is grouped using the cluster analysis for both directions by the SPSS statistical analysis software^[10]. The cluster results are summarized in Tab. 3.

Tab. 3 Cluster results

Year	North bound direction				South bound direction			
	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 1	Cluster 2	Cluster 3	Cluster 4
2003	1.96	1.44	1.91	2.61	1.11	2.69	1.59	6.83
2004	2.48	2.28	3.00	3.95	1.54	3.51	3.01	8.99
2005	2.82	3.00	3.99	5.05	2.13	3.99	3.82	10.01
2006	3.29	3.99	5.01	6.35	2.82	4.74	5.22	10.34
2007	3.80	5.00	6.46	8.17	3.55	5.37	6.36	11.28
2008	4.44	6.40	8.22	10.05	4.43	6.35	8.22	12.21
2009	5.02	7.55	10.00	12.73	5.39	7.27	9.83	13.46
2010	5.40	8.31	11.03	14.66	5.98	7.60	10.30	14.19
2011	6.55	9.77	12.65	16.52	6.94	9.20	12.04	15.84

It can be seen from Tab. 3 that the rutting data in the north and south directions obtained from the Yanjing highway are divided into four clusters. Cluster 1 suggests that the deterioration rate of pavement rutting over time is very slow, while Cluster 4 suggests that the deterioration process of pavement rutting over time is very rapid. From the cluster results, the rutting deterioration rates for the four clusters are ranked as: Cluster 4 > Cluster 3 > Cluster 2 > Cluster 1. All four clusters are used to establish the pavement rutting prediction model which represents different pavement rutting severities and deterioration rates.

2.3 Grey model development

The GM(1, 1) model is commonly used as a prediction model in the grey system, meaning that there is only one variable in the GM model^[7-8]. The data series should be a time series with comprehensive effect. Therefore, the GM(1, 1) model for time series forecasting is used in this paper for the pavement rutting model development with five steps^[8]:

- 1) Define original data matrix $X^{(0)}$.
- 2) Perform AGO operations on the original data series, defined as $X^{(1)}$.
- 3) Develop the grey coefficient, where the coefficient vector can be expressed as $\hat{a} = \{\alpha, \mu\}^T$.
- 4) Insert grey coefficients into a differential equation. The grey model of AGO data series $\hat{X}^{(1)}(t + 1)$ is developed as

$$\hat{X}^{(1)}(t + 1) = \left(X^{(0)}(1) - \frac{\mu}{\alpha} \right) e^{-\alpha t} + \frac{\mu}{\alpha} \tag{1}$$

- 5) Obtain the estimations of the original data series. The basic computational formula of the GM(1, 1) prediction model is

$$\hat{X}^{(0)}(t + 1) = -\alpha \left(X^{(0)}(1) - \frac{\mu}{\alpha} \right) e^{-\alpha t} \tag{2}$$

Following the five steps described above, the pavement

rutting prediction models using the cluster results for the north bound direction of the Yanjing highway can be obtained, as shown in Tab. 4.

Tab. 4 Grey model for each rutting cluster

Cluster	Grey model	Relative accuracy
1	$R_D(t + 1) = 2.0816e^{0.1347t}$	0.9812
2	$R_D(t + 1) = 2.3164e^{0.1837t}$	0.9210
3	$R_D(t + 1) = 2.988e^{0.1851t}$	0.9238
4	$R_D(t + 1) = 3.6229e^{0.1922t}$	0.9416

Notes: R_D means the pavement rutting depth, mm; t is the time gap of original data series in year.

2.4 Results analysis

The developed pavement rutting models should be validated to determine whether the model is applicable to the rutting data and to explain the data reasonably. Three test methods^[7,10], which are commonly used to evaluate the performance of a grey model, are used in this paper. They are the residual test, the grey relational degree test and the posteriori error test. The residual test and posteriori error test are chosen to test the model because the grey relational degree test is very complex. The assessment criteria of posteriori error test for the GM model are summarized in Tab. 5.

Tab. 5 Assessment criteria of posteriori error test

Grade of model accuracy	P	C
Good	>0.95	<0.35
Fair	>0.80	<0.50
Qualified	>0.70	<0.65
Unqualified	<0.70	>0.65

C and P are two important indicators of the posteriori error test. The smaller the C , the larger the P , the better the grey model. The results of residual test and posteriori error test are calculated, as listed in Tab. 6.

As shown in Tab. 6, the means of relative residual error \bar{e} of the grey models developed in this paper are all less than 10% and the posterior error ratios C are all much smaller than 0.35, indicating that the established

Tab. 6 Results of model accuracy test

GM model	$\bar{e}/\%$	Posterior error ratio C	Grade of model accuracy
1	1.88	0.053	Good
2	7.89	0.076	Good
3	7.62	0.083	Good
4	5.84	0.071	Good

grey models have a high level of accuracy and can meet the requirements of highway pavement maintenance. Therefore, the GM(1, 1) model is reasonable and suitable for predicting the pavement rutting at the project level. The model can describe the rutting deterioration law for most pavement sections.

3 Model Verification

The data sets of north bound direction were used for model development, and the clusters of south bound direction were used for validation of the GM models. Two criteria^[6,8], percentage error and relative root-mean square error (RMSE), are employed in this paper to compare the RD predictions from GM models with the actual RD data. The analysis results between the actual data and GM predictions are presented in Tab. 7.

Tab. 7 Comparison between the actual RD data and GM model predictions

Rutting cluster	Percentage error/%	RMSE
Cluster 1	-0.17	0.31
Cluster 2	3.71	0.35
Cluster 3	-4.66	0.79
Cluster 4	1.24	0.54

The best predictions are observed in Cluster 1 and Cluster 4, in which the deterioration rates of pavement rutting are either very slow or very fast. Meanwhile, the percentage error and RMSE values of each model are small, indicating that the GM models show satisfactory results and provide acceptable project-level pavement performance predictions.

4 Conclusion

This paper presents an experimental study based on the grey theory methodology to develop pavement rutting prediction models. The methodology is proved to be feasible by the case study.

Based on the ANOVA results, the pavement structure does have impact on pavement rutting. Although the influence of the pavement structure on pavement rutting is not significant at early pavement service time, it becomes significant with the growth of pavement service time and cumulative traffic load.

The results of the model tests show that the grey model

established in this study has high accuracy and can meet the requirements of highway pavement maintenance. The model can describe the rutting deterioration trend for almost all pavement sections.

The proposed framework, as demonstrated by the case study, can be applied to a wide range of conditions for various highways. It provides a relatively easy methodology for establishing pavement deterioration models and enhances the decision-making process in highway agencies with limited pavement data, especially at the project level.

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基于灰色理论的高速公路路面车辙预测方法

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摘要:为了制定科学的路面养护决策,提出了一种基于灰色理论的路面性能预测方法.基于路面车辙检测数据,采用方差分析方法研究不同因素对车辙的影响;利用聚类分析方法研究路面车辙发展规律;基于聚类结果,采用灰色理论分类建立了路面车辙灰色预测模型,有效降低了模型的复杂程度.研究表明,轴载和沥青类型对车辙的发展影响最大.所提预测模型精度较高,具有一定的实用价值,能满足高速公路路面养护工程要求,并能较好地解决路面性能预测中的不确定性.

关键词:预测方法;灰色理论;聚类分析;方差分析;路面车辙

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