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Construction of an explicit rutting model for asphalt pavement considering aging factors

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Abstract

Under different time and space conditions, the rutting evolution of asphalt pavement has a complex nonlinear relationship with axle load, temperature, humidity and material. How to express the rutting evolution of asphalt pavement systematically and explicitly has always been a difficult problem in the industry. In this paper, the $I-R-F$ model is proposed for the first time, which can express the rutting evolution of all semi-rigid asphalt pavement forms explicitly. Compared with other mature explicit model frameworks, the structure is more standard, parameters are simplified and the fitting accuracy is higher. The proposed model has improved the rutting fitting accuracy on semi-rigid asphalt roads by an average of 0.018. It is obtained by improving the $R-F$ model framework in the previous research results of the author, introducing the influence factors of ultraviolet aging to correct the model, and further performing Complementary Ensemble Empirical Mode Decomposition with Adaptive Noise and wavelet packet threshold denoising on the RIOHTrack data, ultimately achieving a good fitting effect for rutting evolution.

Keywords: Semi-rigid pavement, Rutting, $I-R-F$ model, Denoising, RIOHTrack



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1. INTRODUCTION

The semi-rigid asphalt pavement has the advantages of high bearing capacity, good anti-deformation performance, strong frost resistance, and ease of local material utilization. Therefore, the semi-rigid asphalt pavement has become the main form of asphalt pavement in many countries. With the development of the transportation industry, the semi-rigid asphalt pavement has exhibited rutting and cracking phenomena. Thus, it is particularly important to study the evolution mechanism of the semi-rigid pavement. Rutting is one of the main failure forms of semi-rigid asphalt pavement, and it is also the main research content of this paper. Rutting increases as traffic loads increase, while rutting deepens longitudinally, further threatening the base and even the subbase. To solve the rutting problem, it is not only necessary to develop anti-rutting materials, but also to analyze related internal and external factors affecting rutting, master its evolution law, further guide pavement design, and solve the rutting problem from the source^[1–3]. Based on the previous work, the corresponding theoretical system has been established in this research field, and it can guide the design better^[4]. However, there are still some practical phenomena, such as lack of data, insufficient data mining and imperfect theoretical system, which lead to some practical difficulties, such as the accuracy of the current asphalt pavement rutting prediction model is not high enough and the design life error of asphalt pavement is large.

Since the 1960s, the research on rutting of asphalt pavements has gradually gained attention and been promoted. The main types of models include mechanical models based on mechanical theories, empirical models driven mainly by data, mechanical-experimental models combining artificial intelligence and mechanical theories, *etc.* The research method of mechanical model is based on elastic layered theory, combined with viscoelastic theory and material performance parameters, the stress and strain law of pavement structure is calculated, and rutting prediction model is obtained. The model forms mainly include viscoelastic model^[5,6], viscoelastic-plastic model^[7,8], viscoelastic-plastic damage model^[9,10] and so on. Although the mechanical model has the strongest theoretical basis, it is difficult to select the mechanical model and accurately confirm the constitutive parameters due to the limitation of practical engineering background and data. The empirical model research method is based on the statistical methods and the actual pavement observation or accelerated loading test data, combined with the actual pavement condition; through statistical regression analysis, the empirical model of asphalt pavement rutting prediction is established. Based on American Association of State Highway and Transportation Officials (AASHTO) test road data, full-scale loop data and indoor loop test data, relevant scholars obtained rut curves of different working conditions and different structures, respectively. In recent years, scholars, through artificial neural network research, also achieved a good rutting prediction effect^[11,12], by combining the machine learning model approach, some explicit model results were obtained^[13]. The rutting prediction model established by empirical model method has good accuracy for specific external environments, pavement structures and materials. However, the practical problems of inaccurate and missing data often cause the empirical model to fail to systematically characterize the rutting evolution process. The mechanical-empirical model method is to establish the empirical relationship equation between rutting depth and pavement structure and material parameters through the mechanical theory of elastic layered system or viscoelastic-plastic system, combined with the relevant indoor and outdoor test data. Based on the research of mechanical theory, the dynamic expression of the stress-strain response model is realized by modifying the test data. The representative prediction models of this model method include Monismith model and AASHTO 2002 model^[14–18]. The mechanical-empirical model combines the advantages of mechanical and empirical methods. The RIOHTrack full-scale ring data used in this paper plays a key role in the implementation of the model. In this paper, the relevant mechanical models are used for reference, and statistical methods are used to fit and modify the model, and finally the corresponding model effect is obtained.

In addition to the mechanical evolution of asphalt pavement under the action of compound force, the aging of asphalt material caused by internal and external factors also has a certain impact on the rutting evolution and research of asphalt pavement. The main factors affecting asphalt aging include external environmental factors such as temperature, air, light and precipitation. Asphalt aging is a gradual process, and the aging rate

directly affects the service life of asphalt pavement. The physical changes and chemical reactions in the aging process of asphalt materials cause bitumen to become brittle and hard gradually, which further affects the deformation resistance and fatigue properties of asphalt binders, thus affecting the durability of the pavement^[19]. Therefore, the durability of asphalt pavement can be improved by analyzing the mechanism of asphalt aging and the relationship between different aging modes and fatigue performance of asphalt pavement, and taking corresponding solutions. Thermo-oxygenation is one of the main processes of aging. In addition to thermal oxygen, ultraviolet (UV) light is another cause of asphalt aging. The main difference between UV aging and thermal oxygen aging is that the way of chemical bond fracture is different. Thermal oxygen causes the thermal decomposition and fracture of the chemical bond inside the polymer material. Under the action of UV, all kinds of chromogenic groups inside the material absorb UV light energy and change from the ground state to the excited state, causing the chemical bond to fracture. The primary oxidation products (such as carboxyl and peroxide groups) produced by UV radiation are unstable, which further accelerates the aging of asphalt. Due to the action of UV light, the internal groups of asphalt molecules are interrupted, and the asphalt components changed^[20,21]. Compared with other aging factors of asphalt pavement caused by rutting, the UV aging factor is more in line with the rutting evolution characteristics of asphalt pavement. Its actual measurement data is easier to collect. Moreover, through data analysis and comparison, its effect is remarkable. Therefore, this paper adopts the UV aging factor for the research. The aging process of asphalt mixture under UV light has the characteristics of saturation state, and the Verhulst model can specifically describe the evolution process of physical properties with the characteristics of saturation state^[22,23]. In this paper, the Verhulst model is used to establish the nonlinear equation of asphalt mixture road performance index under different UV irradiation times.

RIOHTrack is the first full-scale road test ring in China. After years of demonstration, design and construction, the civil construction system of full-scale road test ring road was officially completed in November 2015. The data used in this study is mainly from the RIOHTrack full-scale ring data. The data used in this paper covers temperature, humidity, load, radiation and other data related to rutting research, which was collected after 56 million measurements, and is also the most authoritative full-scale track test data in China^[24]. On the basis of the research of RIOHTrack full-scale ring data, *R-F* model framework was proposed for the first time^[25]. This model method extracts key features in this scenario through machine learning, and is compared with the improved Burgers model and the revised China 2017 specification design model to obtain better prediction accuracy. The *R-F* model has clear expression and strong applicability to semi-rigid asphalt pavement. Without complex data processing and noise reduction, it can achieve a good rutting fitting effect. However, factors such as material evolution and induced rutting inflection points are not considered in the model.

At present, no scholar has been able to effectively propose an explicit rutting evolution model that can effectively represent the rutting evolution law and simultaneously cover the aging mechanism of asphalt materials. In order to anticipate and comprehensively predict the needs of material aging development and rutting and inflection points prediction in advance, this paper innovatively superposes the aging factor into the *R-F* model framework, which was proposed in the previous article^[25]. Through data noise reduction processing and verification, it is found that the effect of the new model is better than most of the current mainstream explicit model frameworks. In this paper, an improved model framework *I-R-F* is proposed for the first time. This research is conducted based on the RIOHTrack full-scale ring road data. The obtained research results have a well-structured format, simple parameters, good fitting accuracy and generalization ability. This model framework has the potential to be further effectively applied to more pavement structures and loading data.

After introducing the research status of asphalt route rutting. In Section 2, the asphalt pavement data denoising method and the superimposed aging mechanism are introduced, and the improved asphalt pavement rutting model *I-R-F* is proposed. In Section 3, based on the semi-rigid asphalt pavement data of RIOHTrack full-scale ring road, a simulation study is carried out and relevant supporting conclusions and results are obtained.

Finally, [Section 4](#) gives a brief summary of this paper.

2. MODEL STUDY

2.1 Theory of denoising analysis

The measured data of RIOHTrack have the characteristics of unknown distribution, high noise and nonlinearity. To better fit the distribution and effectively build the rutting prediction model, it is necessary to perform the denoising analysis on the measured test data.

Commonly used denoising methods include nonlinear median filter, mathematical morphology, singular value decomposition, Empirical Mode Decomposition (EMD), wavelet transform^[26], etc. The signal smoothing effect of the nonlinear median filter is poor. The denoising performance of mathematical morphology filter is determined by its transform type and the shape and size of the structuring element, but the actual pulse signal size is unknown. The smoothness of the signal after singular value decomposition is not good, and the noise content is high after reconstruction. EMD is easy to produce mode aliasing and boundary effects, so that Intrinsic Mode Functions (IMFs) of different scales contain similar components. The power quality signal denoising method based on EMD directly discards the decomposed IMF₁^[27,28]. On the one hand, it cannot retain the high-frequency characteristics of the original signal; on the other hand, it does not consider the influence of end effects and mode aliasing. Ensemble Empirical Mode Decomposition (EEMD) improved from EMD was proposed for signal denoising^[29], although mode aliasing was reduced, it was at the cost of loss of calculation accuracy. The Complementary Ensemble Empirical Mode Decomposition with Adaptive Noise (CEEMDAN), can effectively reduce the reconstruction error^[30].

Wavelet transform is a localized time-frequency analysis tool, which can decompose the signal into wavelet coefficients of different frequency bands, respectively representing the outline and details of the signal. Wavelet transform^[31] only decomposes the low-frequency band of the signal. Wavelet packet transform is a more widely used wavelet transform, which can decompose both low-frequency and high-frequency signals without increasing data redundancy and data loss. The noise of rutting data is mainly distributed in high-frequency signals, so wavelet packet transformation is more effective for denoising rutting data of asphalt roads.

If the first few high-frequency IMFs obtained by EMD decomposition of the noisy power quality signal are directly discarded, it will cause the loss of high-frequency information and incomplete elimination of high-frequency noise. Due to the complex characteristics of asphalt pavement data such as unknown distribution, non-stationary and nonlinearity, the CEEMDAN noise reduction algorithm combined with wavelet packet adaptive threshold is applied in this paper^[32]. CEEMDAN is improved on the basis of EMD, and borrows the idea of adding Gaussian noise in EEMD method and cancelling noise by multiple superposition and average, which is suitable for processing non-stationary and nonlinear signals. Wavelet packet adaptive threshold denoising method combines wavelet packet transform with adaptive threshold to make the data denoising have certain adaptability. The noisy signal is set as follows:

$$y(t) = x(t) + e(t). \quad (1)$$

where $x(t)$ is the original signal, and $e(t)$ is the noise signal.

The overall denoising implementation steps are as follows:

(1) Perform CEEMDAN decomposition on $y(t)$, and obtain IMFs from high to low frequency. The white noise

is generally distributed in the high frequency component.

- (2) The correlation coefficient method is used to screen out the first few IMFs components that need to be denoised by wavelet packet adaptive threshold.
- (3) Threshold noise reduction is performed on the sieved IMFs.
- (4) The signal after threshold processing is reconstructed with the remaining IMFs, and the denoised signal is obtained.

2.2 Improved R-F model

The *R-F* model framework is constructed by analyzing the data of RIOHTrack road, using machine learning to extract the key features that affect rutting, and further referring to the index empirical model^[25]. This model frame takes the cumulative axle load as the main independent variable, and the rutting evolution process of semi-rigid asphalt pavement is easily and systematically fitted. The form of the model is an exponential function under the action of cumulative axial load, and the specific expression is given in

$$RD = \sum_{k=1}^b a_k N_s^k. \quad (2)$$

where *RD* is the rutting data, and unit is 0.1mm; *b* and *a_k* are the model coefficients; *N_s* is the logarithmic expression of cumulative axial load on asphalt pavement.

R-F model framework has fewer parameter features, standardized model structure, strong convergence and is easy to solve. After continuous analysis and calculation comparison, this model has a balanced effect on all semi-rigid pavement data of Beijing RIOHTrack full-scale ring road, and the fitting effect is better than the existing general model framework. Through model simulation and data analysis, it can be found that this model framework has achieved good results on datasets without noise removal and outlier handling. Moreover, it is applicable to all pavement structures. Therefore, it can be concluded that this model has certain robustness.

The experimental results show that the fatigue life of asphalt pavement will be reduced due to the aging of asphalt material^[33]. With the occurrence of fatigue phenomena such as micro-cracks on asphalt pavement, rutting phenomenon will be intensified under the continuous action of vehicle load. To a certain extent, the aging of asphalt materials accelerates the evolution of rutting, so it is necessary to use asphalt aging as an auxiliary variable to characterize rutting and the aging problem of asphalt pavement needs to be paid attention to.

In order to better study the rutting inflection point effect caused by material aging damage and establish a more universal asphalt rutting evolution model, this paper mainly considers the UV aging factor to conduct supplementary research on road rutting. At the same time, the correlation between thermal oxygen effect and material selection is stronger and more complex, and the relevant measured data is lacking.

In this paper, Verhulst model is used to establish a nonlinear equation characterizing the UV aging properties of asphalt mixture^[34], and the parameters in the model are further estimated. Two characteristic values, UV aging rate and UV aging residual index, are proposed to measure the change of UV aging properties of asphalt mixture, in order to provide theoretical basis for asphalt pavement maintenance and technology.

Because the Verhulst model has a good performance in characterizing the evolution process of saturation states, it is adopted to fit the nonlinear aging process of asphalt mixtures under UV radiation. The Verhulst model is expressed as follows:

$$\frac{dx(t)}{dt} + \alpha x(t) = \beta x^2(t). \quad (3)$$

where $x(t)$ represents the pavement performance index of time t ; both α, β are constant, and $\alpha < 0$.

Solving the above ordinary differential equation, we obtain

$$x(t) = \frac{\alpha}{\beta(1 - Ce^{\alpha t})}. \quad (4)$$

where C is a constant.

When $t = 0$, let $x(0) = x_0$, we can obtain $C = 1 - \alpha/\beta x_0$, then let $\alpha/\beta = k$, then the general solution Equation 4 is transformed into:

$$x(t) = \frac{k}{1 - e^{\alpha t}(1 - k/x_0)}. \quad (5)$$

Let $k/x_0 = UAI$, then Equation 5 is transformed into:

$$x(t) = \frac{UAIx_0}{1 - e^{\alpha t}(1 - UAI)}. \quad (6)$$

which is the nonlinear equation of pavement performance of asphalt mixture under different UV irradiation time.

For Equation 6, when $t \rightarrow \infty$, $x(t) \rightarrow UAIx_0$. Dividing both sides of Equation 6 by x_0 , we obtain:

$$VAI_t = \frac{x(t)}{x_0} = \frac{UAI}{1 - e^{\alpha t}(1 - UAI)}. \quad (7)$$

VAI_t is a ratio, which is the ratio between the aging value of asphalt pavement performance index at time t and the initial value, and it can be called the UV aging residual index of asphalt pavement performance at time t . Based on the research basis and necessity of UV light on asphalt aging, in view of the lack of correlation data between UV light and aging measurement, this paper introduced the VAI_t framework to supplement the rutting prediction framework and improve the rationality of the model mechanism. According to further calculation and study, the VAI_t and UAI_t structures of pavements with different designs differ from the parameter form of the traditional UV aging evolution model, and needs further detailed research and demonstration.

On the basis of R - F model, this paper further considers the influence factors of material aging, studies, demonstrates and improves the rutting of asphalt pavement under the condition of space-time evolution, and carries out noise removal and anomaly processing on the data. By superimposing aging factors, referring to the nonlinear equation of UV aging performance of asphalt mixture constructed by Verhulst model and simulating the equation of asphalt aging process, this paper obtains an improved R - F model framework, which is expressed by I - R - F :

$$RD = \sum_{k=1}^b a_k N_s^k + \beta \cdot \frac{L \cdot R_0}{1 - e^{mt}(1 - L)}. \quad (8)$$

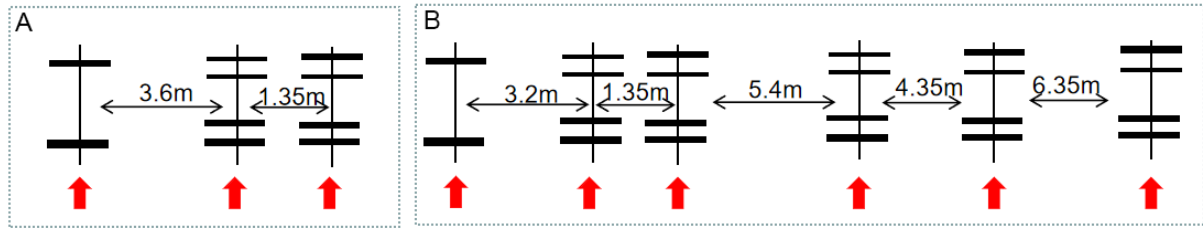


Figure 2. The loading data of the tow truck adopts different axle load wheelbase at different times. (A) shows the loading situation from 2017 to 2018, while (B) represents the loading situation from 2019 onwards.

Figure 1, all have the structural characteristics of semi-rigid asphalt pavement, but the thickness of each layer, the total thickness and the material selection of each layer are different. The data used in the article is prior to October 2021, when more than 56 million measurements were taken.

3.1 Model fitting

Considering the application prospect and data basis comprehensively, this paper selects semi-rigid asphalt pavement data to study. Considering the nonlinear and non-stationary characteristics of asphalt pavement data, this paper adopts the CEEMDAN and wavelet adaptive threshold denoising method.

Under the framework of the improved rutting prediction model 8 for asphalt pavement, according to the data calculation, the paper considers its maximum polynomial degree to be 9, and builds a rutting evolution model for asphalt pavement with axle load:

$$RD = \sum_{k=1}^9 \alpha_k N_s^k + \beta \cdot \frac{L \cdot R_0}{1 - e^{mt}(1 - L)}. \quad (9)$$

where N_s is the logarithmic expression of cumulative axial load on asphalt pavement, β is the aging correlation factor, R_0 is the rutting data at the initial time, $\alpha_k = a \cdots j$, L and m are unknown parameters, and t is time.

Using the above denoised data, the relevant parameters, statistical analysis results and fitting effects are obtained as follows. RD_i represents the rutting evolution model for the i th track, where $i=1, 2, 3, 6, 7, 8$, and 9 , x stands for the axle load, the parameter results obtained by regression are as follows 10-16:

$$\begin{aligned} RD_1 = & 2516341.595 - 2717707.557x + 1206296.577x^2 \\ & - 278568.458x^3 + 34427.579x^4 - 2061.924x^5 \\ & + 69.294x^6 - 11.040x^7 + 1.409x^8 - 0.056x^9 \\ & + 2.428E^{-9} \cdot \frac{1862712486.358R_0}{1 + 1862712485.358e^{-0.211t}}. \end{aligned} \quad (10)$$

$$\begin{aligned} RD_2 = & 3099.3 - 94701.95x + 94182.09x^2 \\ & - 36625.96x^3 + 6075.966x^4 + 1.601x^5 \\ & - 164.655x^6 + 26.77x^7 - 1.853x^8 + 0.0495x^9 \\ & - 3.267 \cdot \frac{1.0259R_0}{1 + 0.0259e^{0.329t}}. \end{aligned} \quad (11)$$

$$\begin{aligned} RD_3 = & -1109109.128 + 1014494.155x - 337668.286x^2 \\ & + 38846.650x^3 + 3371.202x^4 - 1103.186x^5 \\ & + 11.609x^6 + 18.080x^7 - 1.932x^8 + 0.063x^9 \\ & + 0.379 \cdot \frac{17.255R_0}{1 + 16.255e^{-0.2409t}}. \end{aligned} \quad (12)$$

Table 1. The model's effectiveness can be judged based on the coefficient of determination. The maximum value is 0.966, and the minimum value is 0.951

Statistics/track number	1	2	3	6	7	8	9
R^2	0.964	0.963	0.962	0.951	0.962	0.966	0.964
RMSE	2.522	3.360	2.719	2.966	4.567	4.86	3.368
SSE	693.228	1230.617	805.658	958.804	2273.135	2574.807	1236.708
DC	0.964	0.963	0.965	0.962	0.9617	0.9664	0.964
Chi-Square	9.532	13.989	9.569	10.828	23.753	24.673	11.656
F-Statistic	2868.984	2803.308	2717.709	2077.293	2687.691	3078.81	2840.410

Table 2. The coefficients of determination R^2 of each model on these tracks. Compared with different rutting depth prediction models, the improved model in this paper is better than other model frameworks. The closer the R^2 of each pavement structure is to 1, the better the regression effect of the corresponding model is

Models/track number	1	2	3	6	7	8	9
$I-R-F$	0.964	0.963	0.962	0.951	0.962	0.966	0.964
$R-F$	0.935	0.951	0.933	0.935	0.947	0.959	0.947
$R-B$	0.935	0.944	0.905	0.842	0.935	0.899	0.922
$R-2017$	0.912	0.936	0.892	0.885	0.929	0.946	0.910

$$\begin{aligned}
 RD_6 = & 680399.513 - 644469.562x + 231243.731x^2 \\
 & - 33784.806x^3 - 418.826x^4 + 737.110x^5 \\
 & - 75.361x^6 + 0.018x^7 + 0.385x^8 - 0.017^9 \\
 & + 1.24 \cdot \frac{1.00578R_0}{1 + 0.00578e^{0.1579t}}.
 \end{aligned} \quad (13)$$

$$\begin{aligned}
 RD_7 = & 51565.310 - 6572.905x - 30868.739x^2 \\
 & + 19704.752x^3 - 5114.070x^4 + 576.716x^5 \\
 & - 0.004x^6 - 6.743x^7 + 0.637x^8 - 0.019x^9 \\
 & + 1.341 \cdot \frac{1.00000635R_0}{1 + 0.00000635e^{0.483t}}.
 \end{aligned} \quad (14)$$

$$\begin{aligned}
 RD_8 = & 8157.197 + 8468.607x + 6535.877x^2 \\
 & - 16096.160x^3 + 9199.953x^4 - 2614.103x^5 \\
 & + 425.448x^6 - 40.440x^7 + 2.0956x^8 - 0.0458x^9 \\
 & + 0.0212 \cdot \frac{138.572R_0}{1 + 137.572e^{-0.455t}}.
 \end{aligned} \quad (15)$$

$$\begin{aligned}
 RD_9 = & 3087.304 + 345851.563x - 310002.59x^2 \\
 & + 89745.126x^3 + 486.093x^4 - 6299.953x^5 \\
 & + 1631.607x^6 - 197.783x^7 + 12.114x^8 - 0.303x^9 \\
 & + 1.86E^{-9} \cdot \frac{1407738437R_0}{1 + 1407738436e^{-0.406t}}.
 \end{aligned} \quad (16)$$

The performance of the improved model in each road section and the statistics are detailed in Table 1. From the perspective of the determination coefficient value, the model effect is very obvious.

Figure 3-Figure 16 show the fitting performance and residual plot of the rutting evolution model on each semi-rigid asphalt pavement, respectively, and the comparison between the paper model and other excellent models after data denoising is presented in Table 2.

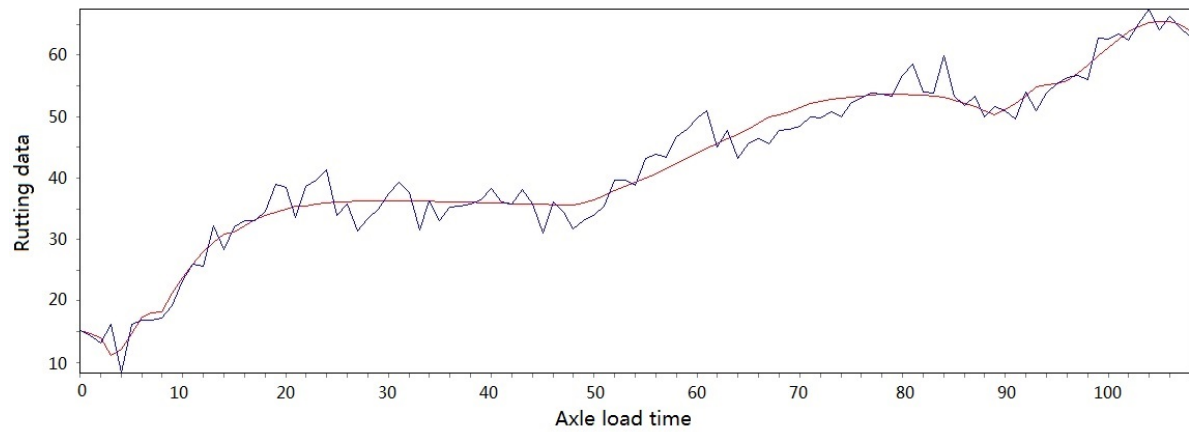


Figure 3. Nonlinear fitting of semi-rigid asphalt pavement STR1.

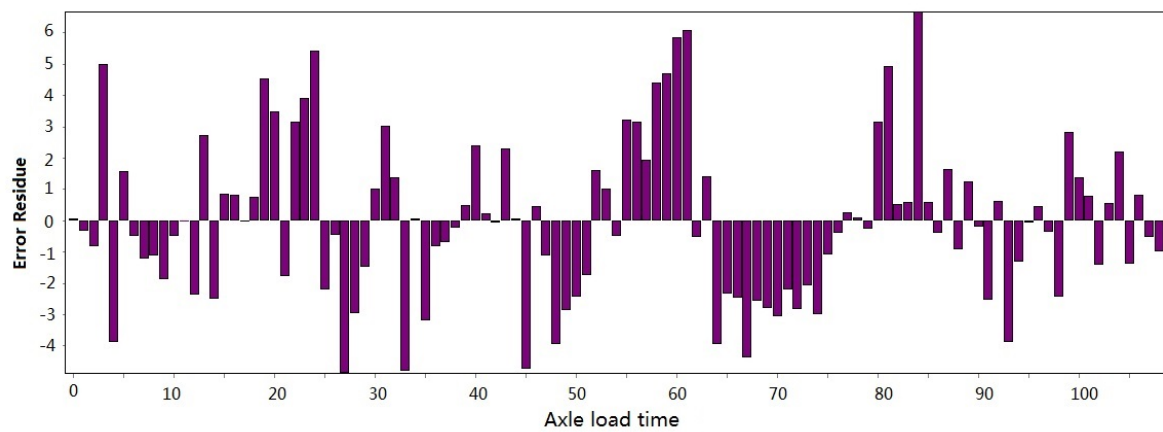


Figure 4. Residual plot of semi-rigid asphalt pavement STR1.

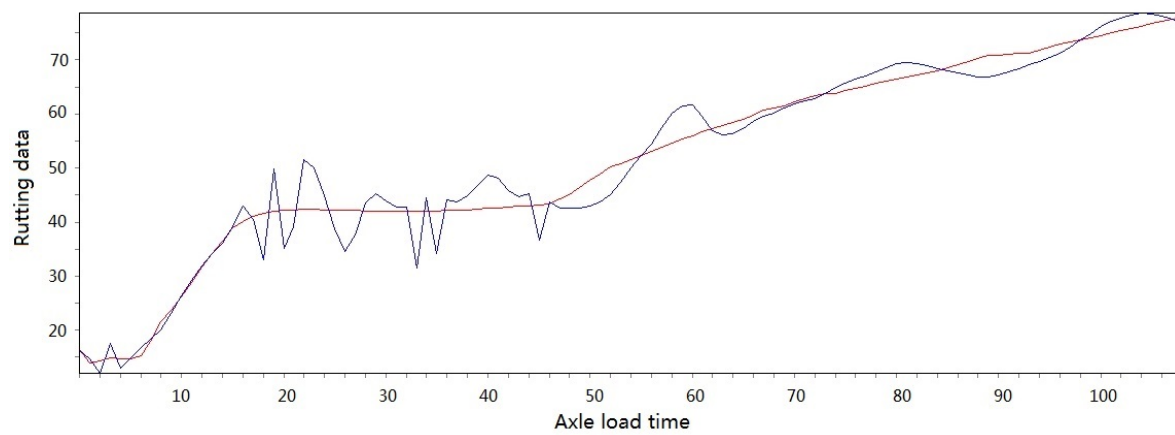


Figure 5. Nonlinear fitting of semi-rigid asphalt pavement STR2.

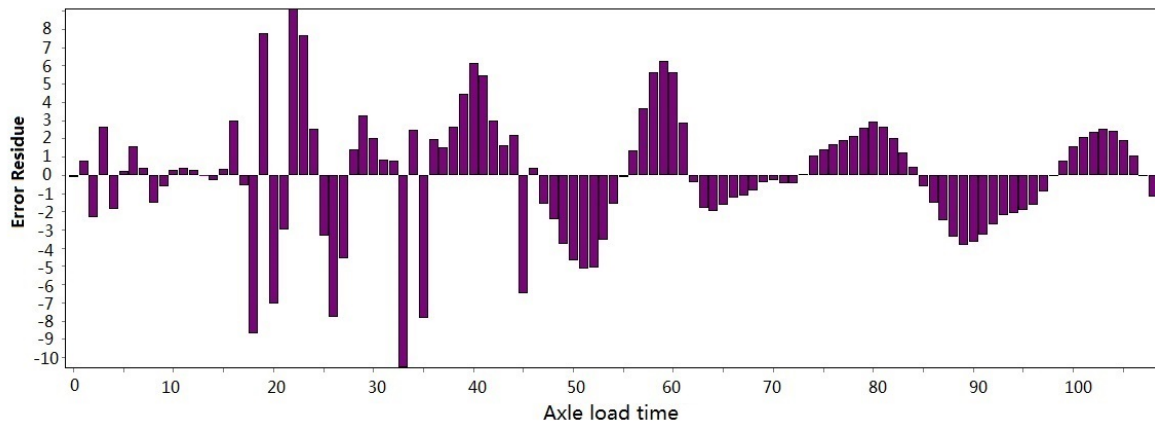


Figure 6. Residual plot of semi-rigid asphalt pavement STR2.

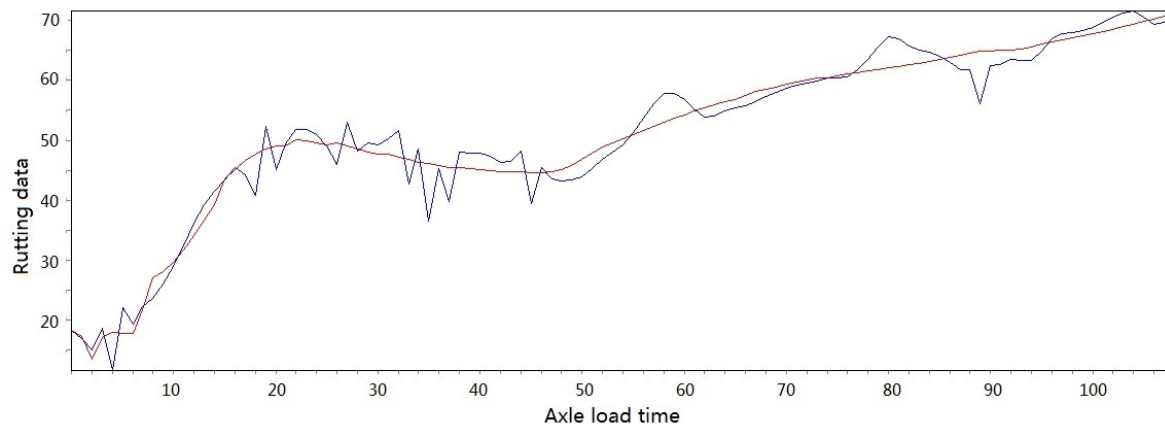


Figure 7. Nonlinear fitting of semi-rigid asphalt pavement STR3.

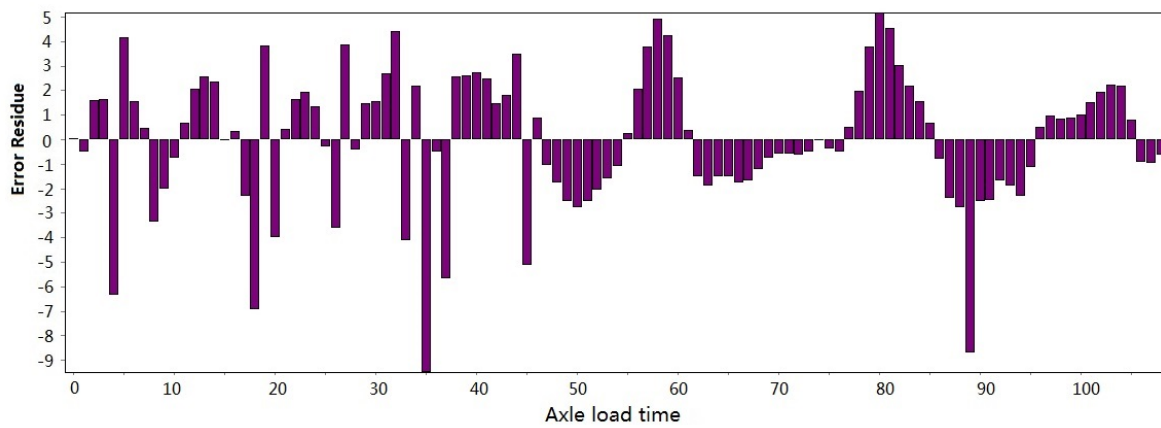


Figure 8. Residual plot of semi-rigid asphalt pavement STR3.

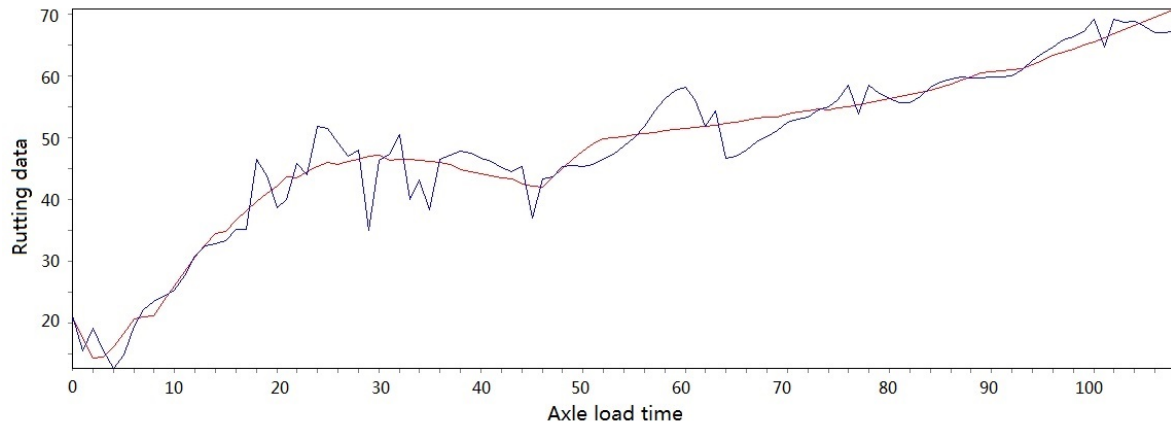


Figure 9. Nonlinear fitting of semi-rigid asphalt pavement STR6.

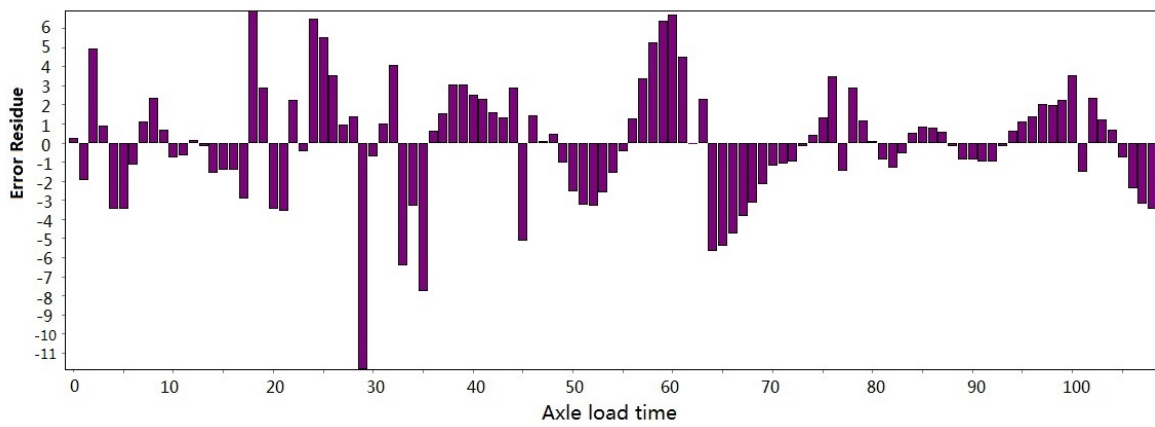


Figure 10. Residual plot of semi-rigid asphalt pavement STR6.

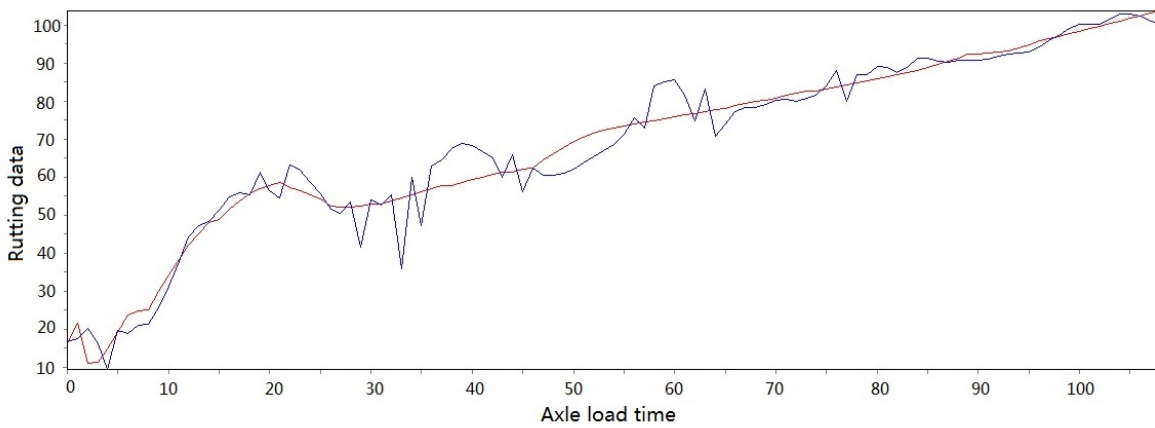


Figure 11. Nonlinear fitting of semi-rigid asphalt pavement STR7.

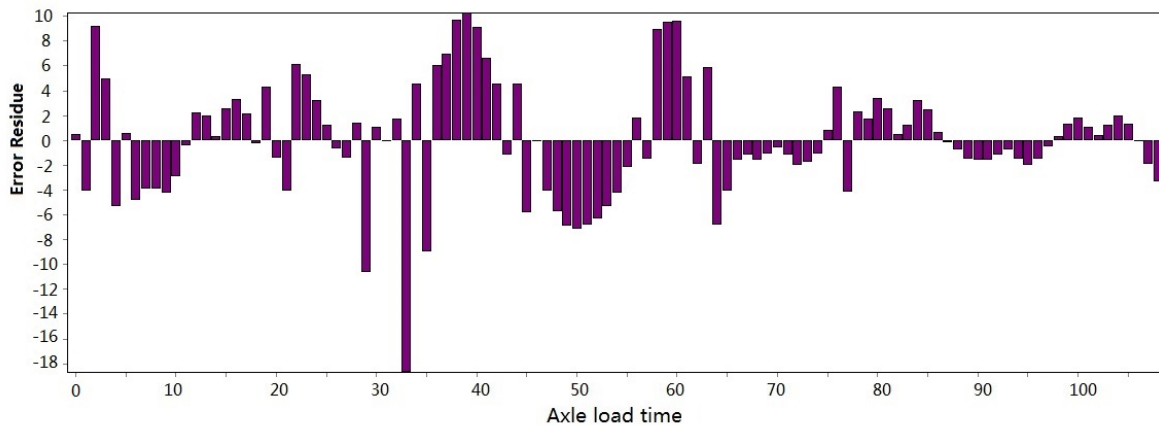


Figure 12. Residual plot of semi-rigid asphalt pavement STR7.

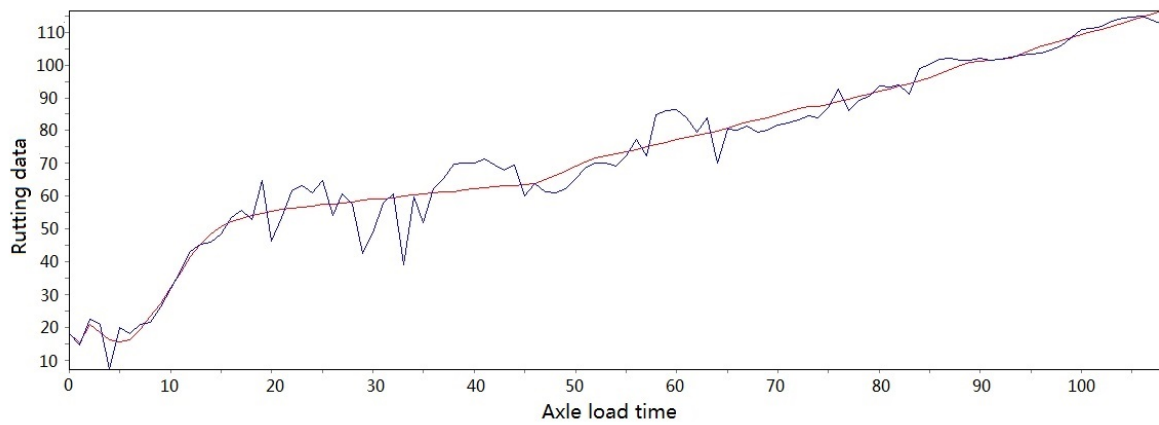


Figure 13. Nonlinear fitting of semi-rigid asphalt pavement STR8.

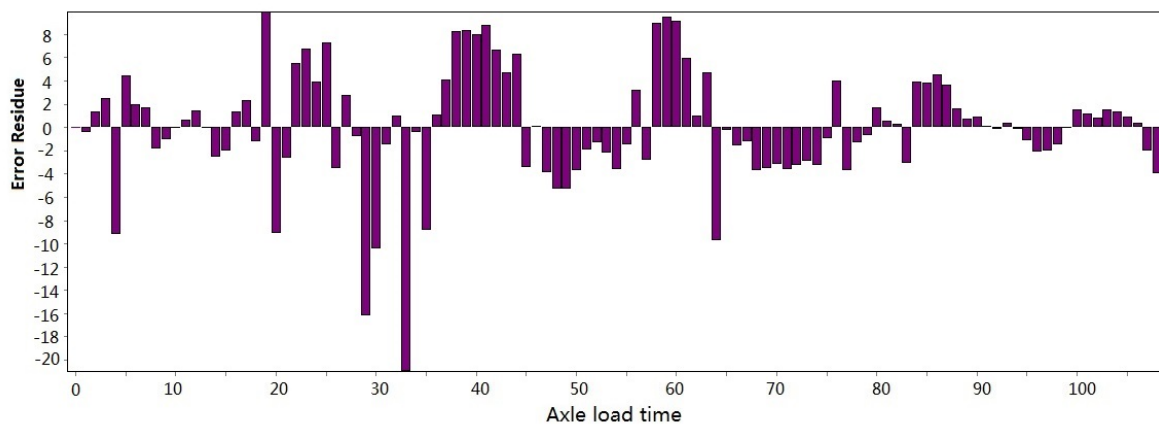


Figure 14. Residual plot of semi-rigid asphalt pavement STR8.

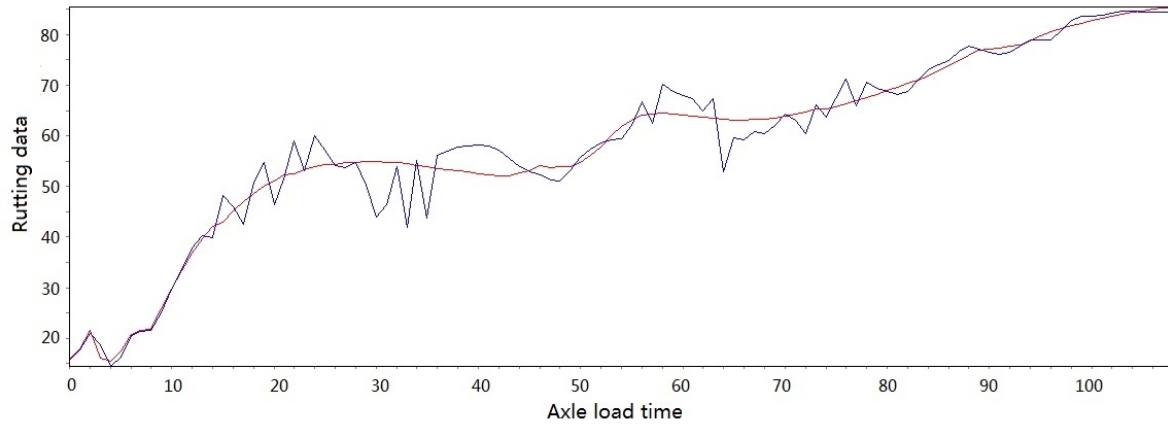


Figure 15. Nonlinear fitting of semi-rigid asphalt pavement STR9.

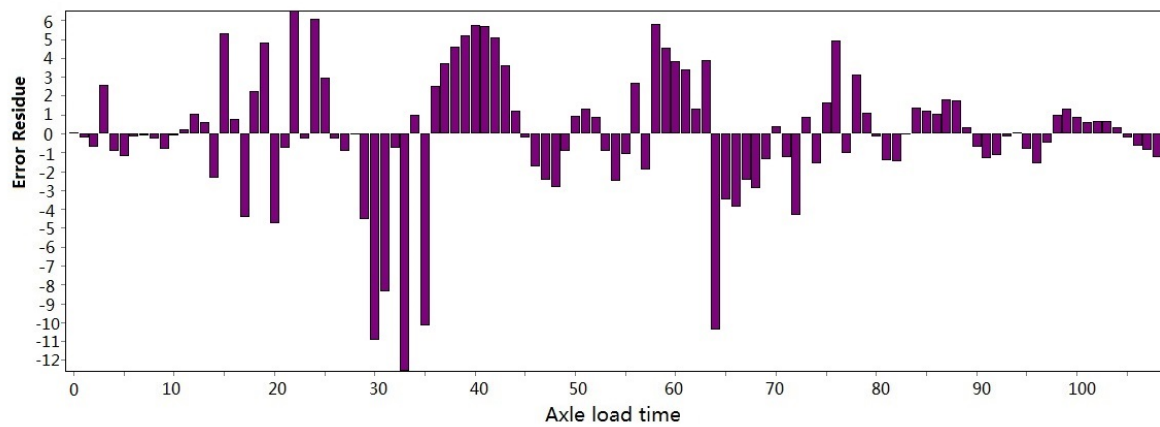


Figure 16. Residual plot of semi-rigid asphalt pavement STR9.

3.2 Convergence analysis

In this section, by setting (17) as the loss function, we further utilize the Levenberg-Marquardt optimization method to effectively fit the evolutionary data.

$$Loss = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}. \quad (17)$$

where, y_i is the actual value, $\hat{y}_i$ is the fitting data.

After calculating and iterating based on the measured rut evolution data, the values of the loss function gradually stabilized on each type of pavement structure. The values were 2.522, 3.360, 2.719, 2.966, 4.567, 4.86, 3.368, respectively. At this point, the model has fully converged, demonstrating the effective convergence effect of the constructed model.

The data calculation and parameter solution in this article were accomplished using a nonlinear programming software. Through this process, the convergence performance of the model was effectively verified.

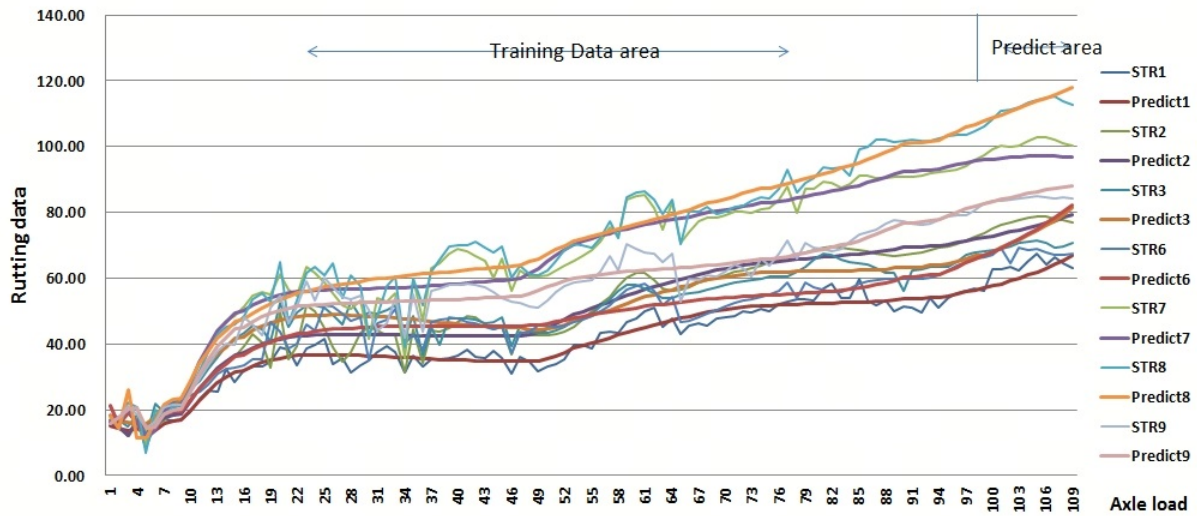


Figure 17. Fitting and prediction effect under the model framework of rutting evolution.

3.3 Prediction effect

In order to verify the model prediction effect, the training set and the test set are divided by time as the boundary. Based on the time axis, the data from the last 10% of the period is selected as the test set, covering 10 samplings from June 2021 to October 2021, with a span of over 7 million standard axle loads and representing the rutting changes over this period. The interval between each two samplings is approximately 770,000 standard axle loads. The training set and test set are divided based on the characteristics and performance of the rutting model.

The specific prediction effect diagram is shown in Figure 17. For the prediction results of unknown domain data, the loss function values reached 3.31, 3.23, 6.55, 8.71, 4.58, 2.61 and 2.19, respectively.

Using the model in this article for data processing and analysis, the obtained determination coefficients are 0.962, 0.965, 0.952, 0.925, 0.959, 0.965, 0.961; the RMSE values are 2.624, 3.288, 3.149, 3.948, 4.774, 4.994, 3.513 and the SSE values are 750.276, 1178.665, 1080.756, 1699.361, 2484.613, 2718.441, 1344.879, reflecting a good prediction effect.

3.4 Comparative analysis

Based on improved Burgers model and the JTG D50-2017 design specification framework, under the actual measurement data, the contents of the improved model framework *R-B* and *R-2017* are introduced in detail reference [25] as follows:

(1) *R-B* model, can well represent the viscoelastic-plastic evolution process of asphalt pavement rutting development [37]. It is achieved by improving the Burgers model, and its specific expression is given in

$$RD_{R-B} = 100 \left[\frac{1}{e^{aT} E_1} + \frac{N_s/10000}{e^{bT} \eta_1} + \frac{1}{e^{aT} E_2} \cdot \left(1 - e^{-\frac{e^{aT} E_2}{e^{bT} \eta_2} (N_s/10000)} \right) + \frac{\Gamma(\sigma - \sigma_s)}{100 e^{bT} \eta_3} (N_s/10000)^n \right]. \quad (18)$$

where

$$\Gamma(\sigma - \sigma_s) = \begin{cases} 0 & \sigma \leq \sigma_s \\ \sigma - \sigma_s & \sigma > \sigma_s \end{cases} \quad (19)$$

RD_{R-B} represents the rutting depth, σ and σ_s denote the stress levels, N_s indicates the cumulative number of standard axle loads, T represents the environmental temperature, E_1 and E_2 represent the elastic modulus, η_1 , η_2 , and η_3 represent the viscosity coefficients, and a and b are the model coefficients.

(2) The R -2017 model is derived by modifying the parameters of the JTG D50-2017 specification. The corresponding parameters are calculated based on the full-scale circular track data. The specific model is given in

$$RD_{R-2017} = aT_{pef}^b P_i^c N_{e3}^d R_{oi}. \quad (20)$$

where P_i represents the vertical stress value, R_{oi} indicates the magnitude of the pressure, T_{pef} signifies the temperature index, and N_{e3} denotes the cumulative number of axle load applications. a , b , c , and d are all regression coefficients.

Through data noise reduction, data analysis, and model parameter fitting, the effect of improved R - F (I- R - F) model 8 is obtained. The coefficients of determination of the proposed model framework under semi-rigid asphalt pavement data are between 0.951 and 0.966. The applicability of the model is extremely high, which is improved compared with other model frameworks such as R - F , R - B , R -2017, and the model effect has reached high fitting accuracy. Under all the data conditions of semi-rigid asphalt pavement structures, the fitting accuracy of this model reached the highest value of 0.966, which is higher than that of other explicit models in all the structures.

4. CONCLUSIONS

In this paper, through data mining and comparative analysis, the value of the I - R - F model is proposed and demonstrated. Given the current limited data conditions and theoretical basis, this paper, through model construction, convergence analysis, and prediction effect research, gradually explored and clarified the significant influence of aging factors on the evolution of rutting. By constructing a rutting evolution model with superimposed aging factors and using the full-scale RIOHTrack data for verification, it is demonstrated that this model has advantages over the existing ones. For all the semi-rigid asphalt pavement structure data, the determination coefficients of the model fitting are all higher than those of the comparison model. The highest value is 0.966, and the lowest is 0.951.

Based on the empirical model of mechanics, this paper innovatively proposes the I - R - F model, and the performance of the relevant model is verified by the measured data. This study gives full play to the advantages of data analysis and material evolution research in mathematics, and improves the theory and model on the basis of the original research, and has achieved good results. Since this model framework performed exceptionally well on the semi-rigid structure data of the RIOHTrack full-scale ring road, it has the potential to achieve good results on other pavement structures. This requires further data-based analysis and verification.

Due to the reasons of basic data and material selection, the aging factor of the improved model has not considered the effect of thermal oxidation, which needs further study and demonstration. At the same time, the model needs to be further validated and analyzed under different road structures, axle loads, temperatures, humidity and radiation environments to further enhance the generalization ability of the model.

DECLARATIONS

Authors' contributions

Substantial contributions to conceptualization and methodology of the study and writing, visualization: Kou, B.; Cao, J.; Shi, Z.

Formal analysis, methodology and validation, along with data analysis: Huang, W.; Ma, T.

Review and editing: Gong, Y.

All authors have read and agreed to the published version of the manuscript.

Availability of data

The data that has been used is confidential.

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Conflicts of interest

This manuscript underwent a double-blind peer review process. Cao, J. is an Advisory Board Member of the journal *Complex Engineering Systems*. Cao, J. was not involved in any steps of editorial processing, notably including reviewers' selection, manuscript handling, and decision making, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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