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Evaluation and Correction Method of Asphalt Pavement Rutting Performance Prediction Model Based on RIOHTrack Long-Term Observation Data

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Abstract: In order to improve the accuracy and reliability of an existing rutting performance prediction model, based on the long-term observation data of the RIOHTrack's full-scale pavement structure, the rutting performance prediction model in China's Specifications for Design of Highway Asphalt Pavement was evaluated, and the model correction method was proposed, which improves the model's reliability and makes it more suitable for rutting estimation in the region. The research found that the rutting model in China's Specifications for Design of Highway Asphalt Pavement has significant structural dependence. The model with the highest prediction accuracy and the smallest error is the semi-rigid base asphalt pavement structure with an asphalt concrete layer thickness of 12 cm; the prediction accuracy of other structures is not high. In order to improve the accuracy and reliability of the rutting prediction model, a new model is established by introducing local correction coefficients into the existing model. After local correction, the accuracy of the rutting prediction models for all structures has been greatly improved, and the determination coefficient R^2 is greater than 0.87. Since the basic data has already reflected the characteristics of different pavement structures and materials, as well as the impact of local climate environment and traffic load conditions, the new model is more suitable for rutting prediction of various pavement structures in the region where the RIOHTrack is located.

Keywords: rutting performance prediction model; long-term observation data; full-scale pavement structure; model accuracy evaluation; local correction coefficient; rutting prediction

Citation: Wu, Y.; Zhou, X.; Wang, X.; Ma, Z. Evaluation and Correction Method of Asphalt Pavement Rutting Performance Prediction Model Based on RIOHTrack Long-Term Observation Data. *Appl. Sci.* **2022**, *12*, 6805. https://doi.org/10.3390/app12136805

Academic Editors: Amir Tabakovic, Jan Valentin and Liang He

Received: 10 June 2022
Accepted: 2 July 2022
Published: 5 July 2022

1. Introduction

Rutting is one of the main diseases of asphalt pavement, and it is also a key design index in the structural design of asphalt pavement in many countries such as: the American Mechanistic-Empirical Pavement Design Guide (MEPDG) [1], the Shell Pavement Design Manual [2], China's Specifications for Design of Highway Asphalt Pavement [3], etc.; all control the structural design through the allowable rutting deformation within the design life. In these design methods, the rutting performance prediction model is mainly used to predict the rutting deformation of the asphalt concrete structure at the end of the design life, and through structural combination and material performance optimization, the rutting deformation at the end of the design life is less than the allowable value, so as to ensure the rationality of pavement structure design. It can be seen that how to ensure the accuracy and reliability of the rutting performance prediction model is one of the key issues of these design methods.

The core basis of the rutting performance prediction model is the conversion relationship between the permanent strain accumulation of the laboratory repeated load test and the actual road rutting accumulation [4,5]. At present, two methods are mainly used to establish the rutting performance prediction model. The first is the layered strain

method [6–11], which combines the mechanical analysis of pavement structure, material performance tests, and actual rutting measurement results of pavement structures, and predicts the rutting deformation according to the layered strain accumulation method. For example, in the MEPDG research [12], Kaloush [13,14] first established the relationship between the permanent strain of each layered asphalt mixture and the number of loading times. Then 387 sets of observation data from 88 LTPP observation sections in 28 states were used to calibrate and verify the relationship, and finally the prediction model for asphalt layer rutting performance [1] was obtained. As for China's Specifications [3], considering the difference of stress distribution at different depths of asphalt pavement and the rutting resistance performance of different layers, the permanent deformation is calculated layer by layer, and based on 229 rutting test results of various asphalt mixtures, a rutting performance model based on the layered strain accumulation method was established, and the model was revised and verified using the rutting data of more than 10 highways and 5 test sections [5]. The Shell Pavement Design Manual [2] uses simplified linear elastic stress analysis and laboratory static load creep tests without confining pressure to establish a model for predicting the permanent deformation of the asphalt layer. The model considers the thickness of the asphalt layer, the average stress in the layer, and the asphalt concrete stiffness, which could compare the resistance to permanent deformation of different asphalt mixtures. Yang [15] introduced the generalized stiffness modulus of the viscosity part of the asphalt layer on the basis of the Shell model, and Finn and Monismith [10] suggested to directly use the asphalt mixture stiffness from the static load creep test under given load stress and temperature conditions, further optimizing the Shell model's rutting estimation equation. Verstvaeten, Ververka, and Francken et al. [16] established a rutting model considering the intermittent time of load action. Zhang et al. [17] established a high-grade asphalt pavement rutting prediction model by using the elastic layered system theory combined with the rheological model of asphalt mixture. Kenis [18] considered that the permanent deformation depends on parameters such as stress, loading time, and temperature, and assumed that the viscoelastic deformation of the asphalt mixture had sufficient recovery time within the load interval, and established a corresponding rutting model accordingly.

The second is the empirical method [19], which directly uses the observation data accumulated over several years to establish the regression relationship between the rutting amount and the relevant influencing variables through statistical analysis. Considering the actual conditions of test sections or field roads and laboratory tests, this method establishes an empirical equation for predicting the relationship between the permanent strain of the asphalt mixture layer and the properties of load and material. Finally, the rutting of the asphalt pavement under long-term repeated loads is determined. For example, Kim et al. [20] used data collected from 930 test points in 39 test road sections in Michigan from 1991 to 1997, and established a rutting prediction model through structure analysis and nonlinear regression analysis, which took into account the correlation between the amount of rutting and the pavement structure, material parameters, and axle loads. Based on the laboratory asphalt pavement analyzer (APA) test, Shami et al. [21] extended to APA test prediction research under different temperatures and axis loads. Through a large number of experiments, Monismith et al. [22,23] obtained an empirical method for rutting prediction; that is, the relationship between rutting and influencing factors. A. Wijeratane et al. [24] established a double-logarithmic model of the relationship between permanent strain and cumulative axis loads. Huang [25] conducted regression analysis on the data through a laboratory loop test, and established an empirical model including the thickness of the asphalt layer and the cumulative axis loads. Because the second method is limited by observation objects and regional conditions, the model is less applicable. Therefore, the first method is mainly used in the design of asphalt pavement in many countries to establish a rutting performance prediction model.

For the prediction model of rutting performance established by the first method, due to the natural environment and loads that the actual pavement structure bears, there are certain differences from the test conditions imposed in the laboratory. It is necessary

to continuously accumulate actual observation data during the service process to make periodic corrections and improvements to the established prediction model [26–33]. Taking the American MEPDG as an example, the first edition of the guide [1] was officially promulgated in 2008, and the rutting prediction model was established based on the observation data and research results at that time. Afterwards, in the process of using this guide, in order to improve the accuracy and reliability of the rutting model, in the second edition of the guide [34] in 2015 and the third edition of the guide [35] in 2020, both of them have made a relatively large revision to the rutting prediction model. Although the model expression remains unchanged, the model parameters are adjusted greatly, and the prediction effect of the rutting performance prediction model after the correction has been greatly improved. The rutting model established by the first method is also used, as well as China's Specifications [3] promulgated in 2017. Due to the late promulgation of the specification, the asphalt pavement designed and opened to traffic in China in accordance with this specification has a longest service life of only 2 years. Due to the lack of long-term observation data of rutting in actual engineering, the effect of using the rutting prediction model is still unknown, and the model cannot be revised and improved periodically.

Therefore, this research uses the long-term observation data of the RIOHTrack's full-scale pavement structures to carry out the accuracy analysis of the rutting performance prediction model in China's Specifications, and proposes a model correction method for the structure with poor model prediction to improve the reliability of the model, and make it more suitable for rutting prediction in the local region. As of April 2022, according to the rutting equivalent conversion principle, the RIOHTrack has completed 51.6 million equivalent single-axle loads (ESALs), which is equivalent to the traffic load level of the expressway heavy traffic level in China's Specification for more than 30 years. The service time of the simulated pavement structure is long enough, and can be used as the basic data to evaluate the accuracy of the rutting prediction model of China's asphalt pavement and propose a correction method.

This research is relatively new work. As mentioned above, after the rutting performance prediction model is established, it is necessary to continuously correct the model according to the long-term observation data accumulated during actual service life, which is very important and practical work. However, there are few asphalt pavements designed and put into operation according to this the newest design specification in China, and long-term observation data cannot be accumulated in the short term, so it is difficult to carry out the work to correct the rutting model. In order to solve this problem, this research analyzes the long-term rutting observation data of the RIOHTrack, and explores a new correction method for the rutting model used by China's Specification. By introducing correction coefficients to locally correct the existing rutting model, the accuracy of the model can be significantly improved. This is of great significance for rutting prediction, and also has important reference value for application in other regions.

2. Objective and Scope

This research aims to evaluate the accuracy of the rutting performance predication model in China's Specifications by using the long-term observation data of full-scale pavement structures and present a model correction method to improve the reliability of the model and make it more suitable for the rutting prediction in the region. The research is mainly carried out on the full-scale test track of the Research Institute of Highway Ministry of Transport (RIOHTrack). A total of 14 kinds of asphalt pavement test sections from 7 categories, including semi-rigid base asphalt pavement, rigid base asphalt pavement, inverted asphalt pavement, and full-depth asphalt pavement with different thicknesses of asphalt concrete materials, are selected as the research object.

3. Methods

This research is mainly carried out on the RIOHTrack, which was completed in October 2015, and has been officially in operation for loading tests since December 2016. To date,

the RIOHTrack has been in operation for more than 5 years for accelerated loading tests using real vehicles. As heavy trucks are used for the accelerated loading test, according to China's Specifications, each axle load of the truck should be converted into the cumulative number of equivalent standard axle loads (10 t) to characterize the traffic load level and correspond to the design service life of the pavement structure. During the test, heavy trucks are used for accelerated loading. Given that the pavement structure simulated by the RIOHTrack accelerated loading test has been in service for long enough, the accuracy of the rutting prediction model of asphalt pavement in China can be evaluated on the basis of the evolution data of the pavement structure rutting depth obtained during accelerated loading tests, and the correction method is proposed.

4. Overview of RIOHTrack Full-Scale Pavement Test Track

The RIOHTrack, for which this research based, is the first full-scale pavement test track of road fields in China. It is located in Beijing, where the average air temperature of the coldest month is −4.6 °C and the average air temperature of the hottest month is 25.8 °C. The RIOHTrack, with a total length of 2039 m, is an enclosed curve composed of straight lines and circular curves, with a north–south trend and a symmetrical arrangement. The long-term observation data of each pavement structure of the RIOHTrack is selected to carry out the model accuracy analysis, for several reasons. First, various pavement structures paved by the RIOHTrack are very representative in China, basically covering more than 90% of the commonly used pavement structure types on the asphalt pavement of China's expressways. Moreover, each test section of the RIOHTrack was constructed with the same structure thickness, pavement material, and construction technology as the actual project. The width of each test section is 7.5 m, and two inner and outer lanes are set; each lane is 3.75 m wide, the section length is 50–60 m, and the test size is also completely consistent with the actual engineering project. Therefore, these test structures can better reflect the real situation of actual engineering projects, and the performance observations carried out on this basis are also well representative. Second, the evaluation and accuracy analysis of the rutting model requires the support of long-term service performance observation data. We know that the evolution of pavement service performance is a long-term process. If calculated according to natural life, the service life of pavement usually reaches several decades, which is too long for model verification, and it is difficult and impractical to obtain continuous observation data for decades. The RIOHTrack is a very efficient accelerated loading test platform with the ability to simulate long-term performance in short-term tests. It accelerates the service performance of pavement by increasing the test load of the vehicle. According to the axle load conversion equation, it can be known that each time the test load of the existing RIOHTrack acts once, it is equivalent to dozens or hundreds of times the ESAL of 10 t acts. In this way, the simulation of the long-term service performance of pavement can be realized in the short term. These long-term performance observations can be used to verify the model.

Structure I is a semi-rigid base pavement with an asphalt layer thickness of 12 cm, and the structure numbers are STR1 and STR2. Structure II is rigid base asphalt pavement, the structure numbers are STR4 and STR5. Structure III is a semi-rigid base pavement with an asphalt layer thickness of 18 cm, and the structure numbers are STR7 and STR8. Structure IV is inverted asphalt pavement, and the structure numbers are STR10 and STR12. Structure V is a semi-rigid base pavement with an asphalt layer thickness of 24–28 cm, and the structure numbers are STR11 and STR13. Structure VI is a semi-rigid base pavement with an asphalt layer thickness of 36 cm, and the structure numbers are STR16 and STR17. Structure VII is full-depth asphalt pavement, and the structure numbers are STR18 and STR19 [36–39].

The RIOHTrack layout is shown in Figure 1, and the structure is shown in Figure 2. In the base layer shown in Figure 2, CBG25-I and CBG25-II are cement-bonded graded aggregate material, and the 7-day unconfined compressive strengths are 6 MPa and 4.5 MPa, respectively. CS is cement-stabilized soil, and the 7-day unconfined compressive strength

is 2 MPa. LCC and CC are lean cement concrete and cement concrete, respectively. GA is graded aggregate.

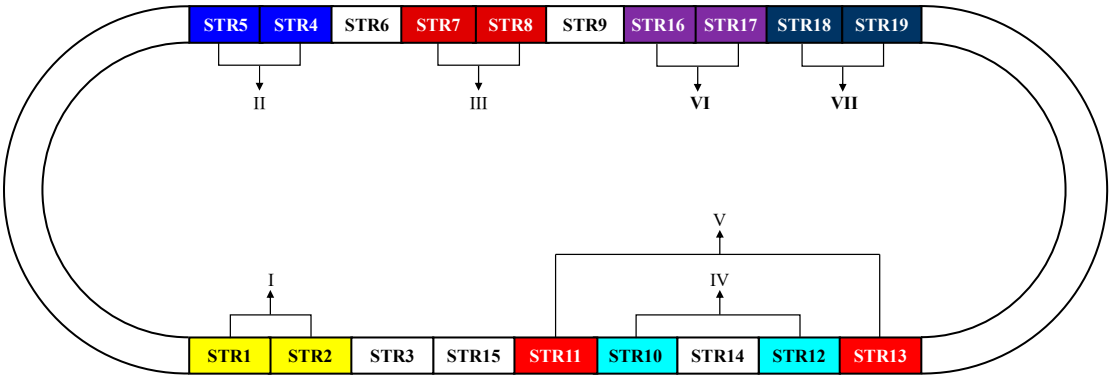

Figure 1. The RIOHTrack layout.

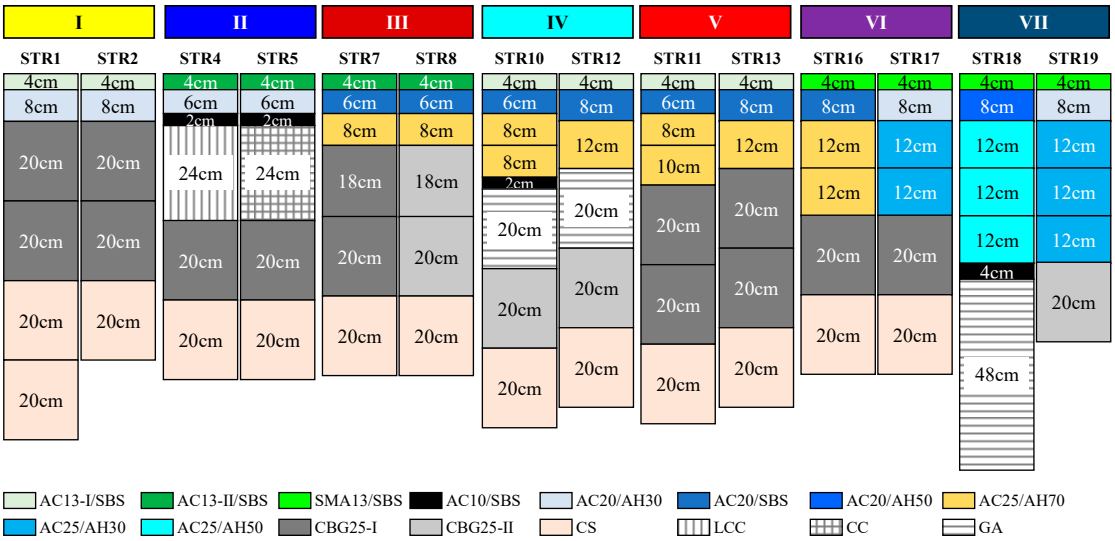

Figure 2. The RIOHTrack structure.

To ensure test efficiency, heavy trucks are used for the accelerated loading on the RIOHTrack. From December 2016 to December 2018, loading mode I is adopted for loading. The loading vehicles include four three-axle trucks (Figure 3). Since January 2019, loading mode II is adopted for loading. The loading vehicles, including six six-axle trucks, are updated, as shown in Figure 4. The test loading efficiency is increased to more than 3 times that of loading mode I. The axle load of the loading vehicles is heavy, more than 10 t, the standard axle load stipulated in China's Specifications. Therefore, it is necessary to convert it into the cumulative number of ESALs taking the rutting as a design indicator based on Equation (1). Based on this, the cumulative number of ESALs in RIOHTrack loading tests has been 51.60 million from December 2016 to April 2022, as shown in Figure 5.

$$N_e = C_1 C_2 \left(\frac{P_i}{10} \right)^4 \tag{1}$$

where C_1 refers to the axle-number coefficient of converted vehicles, converted according to the rutting equivalence principle; when the distance between the front and rear axles is greater than 3 m, take 1. when the distance between the front and rear axles is less than 3 m, take 1.05; C_2 refers to the wheel-set coefficient of converted vehicles. 1.0 for double wheels and 4.5 for single wheels; and P_i refers to the axle load of the converted vehicles (t).

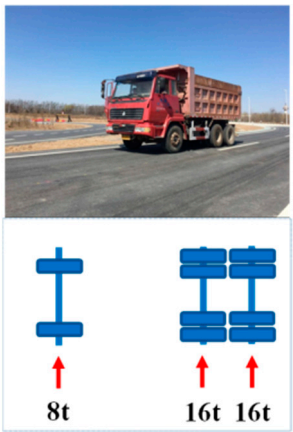

Figure 3. Axle load and axial distribution of trucks in loading mode I.

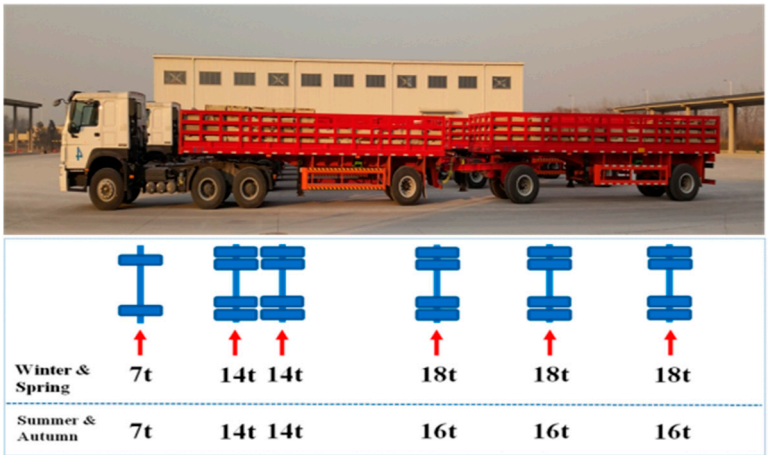

Figure 4. Axle load and axial distribution of trucks in loading mode II.

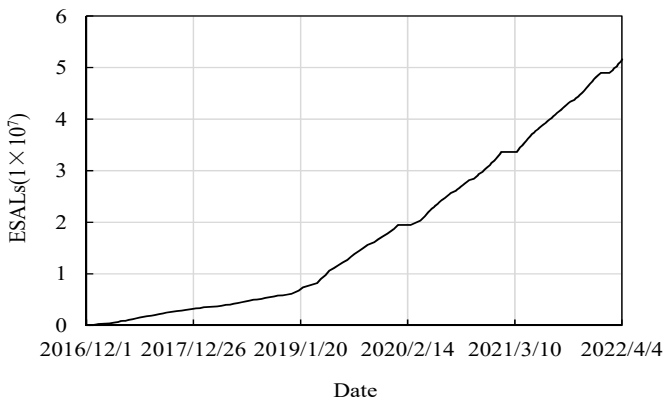

Figure 5. Curves of the cumulative number of equivalent single-axle loads.

5. Rutting Prediction Model and Parameter Values of China's Asphalt Pavement

The rutting performance prediction model in China's Specifications is established by the cumulative permanent deformation. First, each asphalt mixture layer is layered, and then according to the rutting test under standard conditions, the rutting permanent deformation of each layer of asphalt mixture is obtained, and the permanent deformation of each layer and the total permanent deformation of the asphalt mixture layer are calculated, so as to achieve the purpose of controlling the structure design. The rutting performance prediction model expressions are shown in Equations (2) and (3).

$$R_a = \sum_{i=1}^{n} R_{ai} \tag{2}$$

$$R_{ai} = 2.31 \times 10^{-8} k_{Ri} T_{pef}^{2.93} p_i^{1.80} N_e^{0.48} R_{0i} \tag{3}$$

where R_a is the permanent deformation of the asphalt mixture layer (mm); R_{ai} is the permanent deformation of the i-th layer (mm); R_{0i} is the permanent deformation of the i-th layer of the asphalt mixture in the laboratory rutting test at 60 °C (mm); N_e is the cumulative number of ESALs; T_{pef} is the rutting equivalent temperature of the asphalt mixture layer (°C); p_i is the vertical compressive stress on the top surface of the i-th layer (MPa); k_{Ri} is the comprehensive correction coefficient, calculated according to Equations (4)–(6); z_i is the depth (mm) from the midpoint of the i-th layer to the road surface; and h_a is the thickness of the asphalt mixture layer (mm); when it is greater than 200 mm, take 200 mm.

$$k_{Ri} = (d_1 + d_2 \cdot z_i) \cdot 0.9731^{z_i} \tag{4}$$

$$d_1 = -1.35 \times 10^{-4} h_a^2 + 8.18 \times 10^{-2} h_a - 14.50 \tag{5}$$

$$d_2 = 8.78 \times 10^{-7} h_a^2 - 1.50 \times 10^{-3} h_a + 0.90 \tag{6}$$

Since the long-term evolution data of rutting in this research is obtained based on the RIOHTrack full-scale pavement test track, the traffic loads on each pavement structure are exactly the same, so the N_e of each structure should take the same value for rutting prediction, which can be taken according to Equation (1) and Figure 5.

According to the regulations in China's Specifications, T_{pef} is related to the temperature in the region where the pavement structure is located and the thickness of the asphalt mixture layer. It can be seen from the calculation that for the STR1, STR2, STR4, and STR5 in this research, the equivalent temperature of the rutting is 22.02 °C; the equivalent temperature of rutting of STR7 and STR8 is 22.98 °C; and the equivalent temperature of rutting of STR10, STR12, STR11, STR13, STR16, STR17, STR18, and STR19 is 23.30 °C.

There are 10 kinds of asphalt mixtures in the structures of this research. The test results of the permanent deformation of each asphalt mixture in the laboratory rutting test at 60 °C are shown in Table 1. The value of R_{0i} can be selected according to Table 1. In addition, p_i and k_{Ri} can be calculated according to the layered model of each pavement structure, and calculated according to the mechanics of the elastic layered system and Equations (4)–(6), and will not be repeated here.

Table 1. Permanent deformation of asphalt mixture rutting test.

AC Type	AC10	AC13-I	AC13-II	SMA13	AC20	AC20	AC20	AC25	AC25	AC25
Asphalt Type	SBS	SBS	SBS	SBS	AH30	AH50	SBS	AH30	AH50	AH70
Permanent Deformation (mm)	2.40	1.54	1.65	1.82	1.70	2.67	1.30	1.96	2.12	2.82

6. Results and Discussion

6.1. Evaluation on Asphalt Pavement Rutting Prediction Model

Figure 6 shows the comparison between the predicted value of the model and the measured value during the long-term evolution of rutting of seven categories of structures. To evaluate the accuracy and prediction effect of the rutting prediction model quantitatively, the mean square error (MSE), root mean square error (RMSE), mean absolute error (MAE), mean relative error (MAPE), coefficient of determination (R^2), and other indicators between the predicted value of the rutting model and the measured value are calculated and summarized in Table 2.

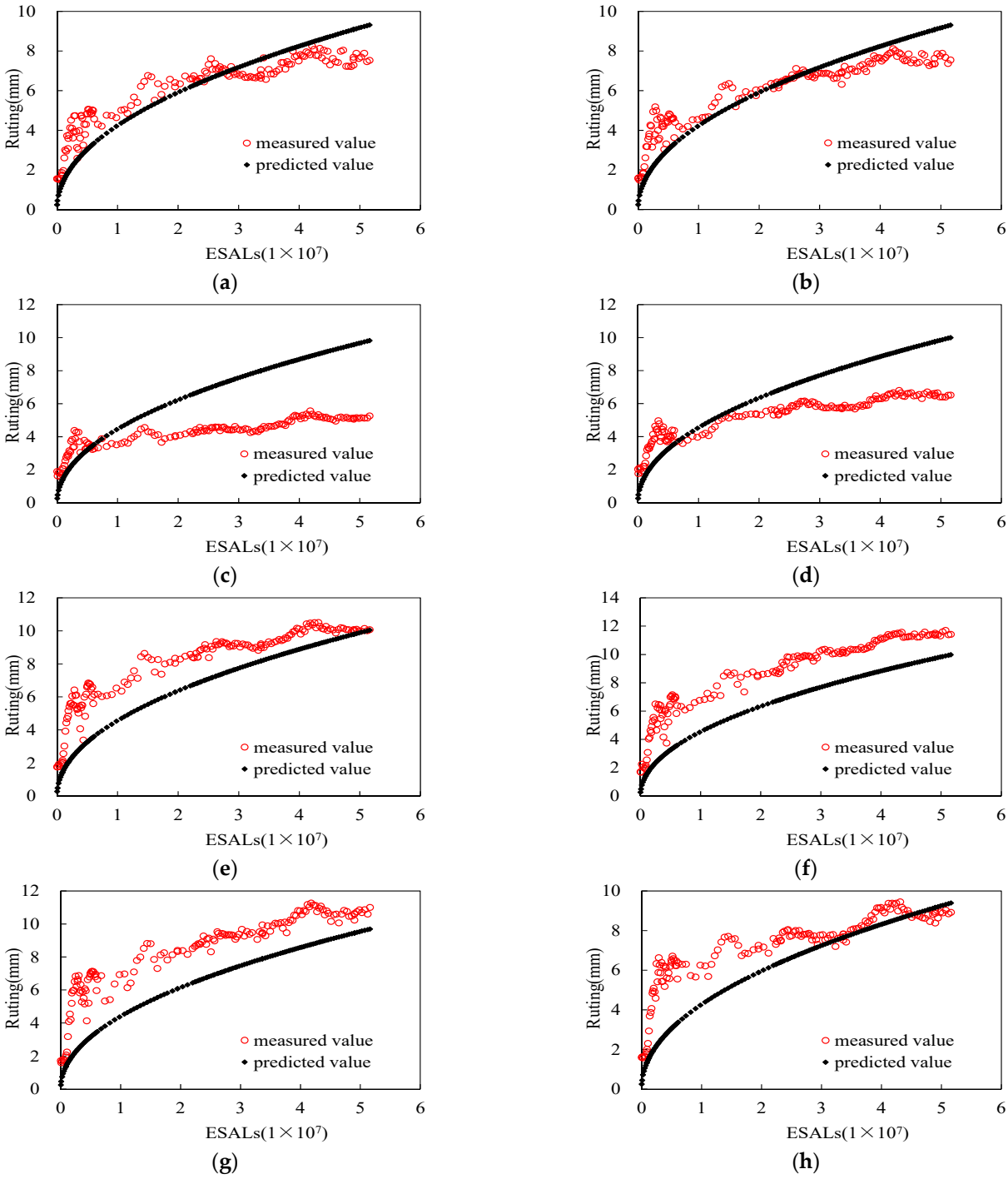

Figure 6. *Cont.*

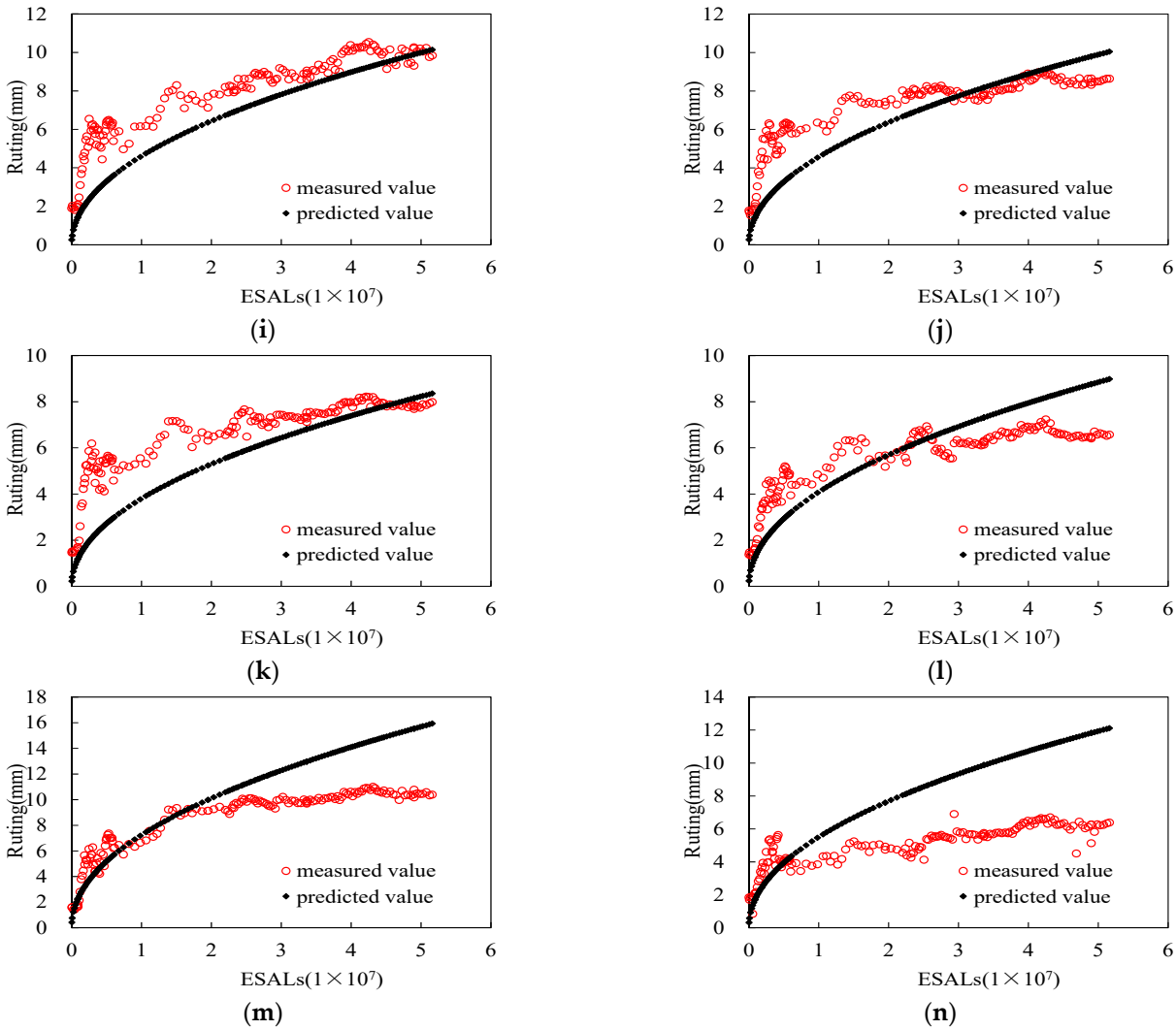

Figure 6. Comparison between the predicted value of the model and the measured value. (**a**) Structure I-STR1. (**b**) Structure I-STR2. (**c**) Structure II-STR4. (**d**) Structure II-STR5. (**e**) Structure III-STR7. (**f**) Structure III-STR8. (**g**) Structure IV-STR10. (**h**) Structure IV-STR12. (**i**) Structure V-STR11. (**j**) Structure V-STR13. (**k**) Structure VI-STR16. (**l**) Structure VI-STR17. (**m**) Structure VII-STR18. (**n**) Structure VII-STR19.

Table 2. Error between the predicted value of the rutting model and the measured value.

Structure Type		MSE	RMSE	MAE	MAPE	R^2
Unit		mm^2	mm	mm	-	-
I	STR1	1.16	1.08	0.91	18.3%	0.6346
	STR2	1.12	1.06	0.85	17.6%	0.6223
II	STR4	7.70	2.78	2.40	53.7%	−8.2491
	STR5	3.67	1.92	1.69	32.1%	−1.2133
III	STR7	3.52	1.88	1.64	25.2%	0.3337
	STR8	5.68	2.38	2.29	30.9%	0.2222
IV	STR10	5.63	2.37	2.20	30.5%	0.0469
	STR12	3.09	1.76	1.35	23.0%	0.0860
V	STR11	2.89	1.70	1.43	23.1%	0.4220
	STR13	2.45	1.56	1.26	21.8%	0.2500
VI	STR16	2.67	1.63	1.31	24.4%	0.0444
	STR17	1.72	1.31	1.15	23.1%	0.2084
VII	STR18	7.23	2.69	2.20	25.3%	−0.0792
	STR19	5.51	2.35	2.01	31.8%	−1.0787

It can be seen from Figure 6 and Table 2 that:

(1) For Structure I, the predicted value of the rutting model is relatively close to the measured value. The measured result fluctuates up and down near the prediction curve, and the error of the model prediction is small. For STR2 with the smallest error, the MSE is 1.12 mm^2; the RMSE is 1.06 mm; the MAE is 0.85 mm; and the MAPE is 17.6%. The R^2 of STR1 and STR2 rutting models are 0.6346 and 0.6223, respectively. According to [12], the R^2 of the predicted value of the model and the measured value in MEPDG is 0.6425. For Structure I, the accuracy of the rutting model in China's Specifications is basically equivalent to that in American MEPDG, and the model has a similar prediction effect.

(2) For Structures II and VII, the correlation between the predicted value of the rutting model and the measured value is similar. A great difference is observed between the predicted value and the measured value of the rutting model with the two categories of structures. The predicted value is significantly larger than the measured value. The predicted curve is above the measured value. In addition, with the increase in the cumulative number of ESALs, the error in the model prediction rises. For STR5 with the smallest error, the MSE is 3.67 mm^2; the RMSE is 1.92 mm; the MAE is 1.69 mm; and the MAPE is 32.1%. The R^2 of STR4, STR5, STR18, and STR19 structural rutting models, namely, −8.2491, −1.2133, −0.0792, and −1.0787, respectively, are all negative. According to the meaning of the determination coefficient R^2, when R^2 is negative, the effect of the simulated prediction is poor and even cannot reach the prediction accuracy of the average value curve of the measured value. Therefore, for Structures II and VII, the accuracy of the rutting model in China's Specifications is relatively poor. This model is not suitable for the rutting prediction. The reason for this phenomenon may be that the characteristics of the two structures are not fully considered when Equation (3) is established, thereby resulting in the poor prediction effect of the model. Figure 2 shows that Structure II belongs to the rigid base asphalt pavement. The lean concrete or cement concrete is adopted for the base, and the modulus and strength of the base are relatively high in value. Structure VII belongs to the full-depth asphalt pavement structure with the thickness of asphalt materials reaching 48–52 cm. According to [3], the rutting model in China's Specifications is established on the basis of the rutting data of 10 highways and 5 test sections. Semi-rigid materials are used as the base or subbase of more than 95% of asphalt pavement in China, and the thickness of the asphalt concrete structural layer generally does not exceed 30 cm. Therefore, to make the rutting model in the design specification more widely applicable, semi-rigid materials are used as the base in the construction of 10 highways and 5 test sections used in the model, and the thickness of the asphalt concrete is in the range of 16–28 cm. When establishing Equation (3), Structure II, which has lean concrete or cement concrete as the base, and Structure VII, which has 48–52 cm-thick asphalt material layer thickness, are not considered, which is also the main reason for the poor prediction effect of Equation (3) on the two kinds of structures.

(3) For Structure III and STR10 in Structure IV, the predicted value is significantly larger than the measured value. The predicted curve is below the measured value. After the initial loading stage (N_e is about 5 million), the predicted curve is basically parallel to the measured curve, and the difference between the predicted value and the measured value is basically constant with the increase in cumulative ESALs. For STR7 with the smallest error, the MSE is 3.52 mm^2; the RMSE is 1.88 mm; the MAE is 1.64 mm; and the MAPE is 25.2%. The R^2 of STR7, STR8, and STR10 structural rutting models are 0.3337, 0.2222, and 0.0469, respectively. R^2 is in the range of 0–0.4. The prediction effect is not ideal.

(4) For the remaining structures, namely, STR12 in Structures IV, V, and VI, an intersection between the model prediction curve and the measured curve of the rutting model exists with the increase in ESALs. Therefore, it can be obviously divided into two stages.

The first stage is the first section of the whole rutting evolution curve. When the ESALs reach a certain critical value (N_e') from 0 at the beginning, the predicted value of the rutting model is obviously less than the measured value. However, with the increase in ESALs, the error of the model prediction gradually becomes small. When it reaches the critical value (N_e') of ESALs, the predicted value is almost the same as the measured value. The second stage is the latter section of the whole rutting evolution curve. When the number of ESALs is greater than the critical value (N_e'), the predicted value of the rutting model is higher than the measured value. With the increase in ESALs, the model prediction error gradually rises. For different structures, the critical values (N_e') of ESALs vary greatly. For STR17 with the smallest error, the MSE is 1.72 mm^2; the RMSE is 1.31 mm; the MAE is 1.15 mm; and the MAPE is 23.1%. The critical values (N_e') of STR12, STR11, STR13, STR16, and STR17 are 35 million, 50 million, 30 million, 45 million, and 25 million, respectively. The R^2 of five structural rutting models are 0.0860, 0.4220, 0.2500, 0.0444, and 0.2084. R^2 is in the range of 0–0.5. The prediction effect is not ideal. From the meaning of the R^2, although the rutting model can be used to predict these structures with R^2 between 0 and 0.5, the accuracy is not high. The main reason is that the rutting observation data in this research are based on the RIOHTrack accelerated loading test. Compared with 10 highways and 5 test sections used for establishing the model in China's Specification, some differences are observed in the geographical location, climate environment, and traffic load, etc. A local correction coefficient should be introduced into the rutting model by referring to [26–33], and the model must be modified to obtain a rutting prediction model suitable for the location of the RIOHTrack, thereby improving the accuracy of model prediction.

According to the equivalence relationship between the design life and the cumulative ESALs in China's Specification, under the heavy traffic load level, the expressway with a 30-year design life is equivalent to more than 50 million cumulative ESALs of pavement. Table 3 summarizes the measured rutting values and model-predicted values of each pavement structure of the RIOHTrack under the cumulative 50 million ESALs in Figure 6. From the data in Table 3, it can be seen that, at the end of design life, the structures with the largest difference between the measured rutting values and the model predicted values are Structure II and VII, which are also predicted poorly in Table 2. Furthermore, STR7 and STR11 have the smallest difference between the measured rutting values and the model predicted values. However, from the rutting evolution curve in Figure 6, the rutting model has the highest prediction effect only when it reaches the end of design life. The prediction effect of the whole life cycle is not ideal, which is basically consistent with the results of the previous analysis.

Table 3. Rutting values at the end of design life.

Structure Type	I		II		III		IV		V		VI		VII	
	STR1	STR2	STR4	STR5	STR7	STR8	STR10	STR12	STR11	STR13	STR16	STR17	STR18	STR19
RIOHTrack Measured values (mm)	7.70	7.89	5.15	6.40	9.99	11.60	10.69	8.90	10.05	8.50	7.89	6.63	10.45	7.36
Model Predicted Values (mm)	9.20	9.19	9.69	9.87	9.91	9.85	9.57	9.28	10.02	9.91	8.25	8.86	15.72	11.96
MAPE (%)	19.5	16.5	88.1	54.2	0.8	15.1	10.5	4.3	0.4	16.6	4.5	33.8	50.5	62.5

The aforementioned analysis results show that the rutting model in China's Specifications has significant structural dependence. Some problems are encountered in using a unified rutting model for the prediction of different structures, especially for rigid base and full-depth asphalt pavements. The rutting evolution process of the two structures is not considered when the model is established, so the prediction effect of the model on both structures is poor. To ensure the prediction accuracy of the rutting model, we should correct, improve, and optimize the established rutting model combined with the long-term

evolution data of rutting deformation of pavement structure with load and environment according to the characteristics of the pavement structures and materials in different areas, as well as the geographical location, climate environment, and traffic load, to improve the prediction accuracy. Finally, a high-precision rutting prediction model suitable for different pavement structures and areas is obtained.

6.2. Correction of Asphalt Pavement Rutting Prediction Model

To ensure the wide applicability of the rutting prediction model in China's Specifications and the model in MEPDG, the measured rutting data from actual projects and test tracks in different regions of the country were used in establishing the model. As a result, the applicability is ensured, but the prediction accuracy of the model is limited. As shown in [12], when R^2 is higher than 0.60, the prediction effect of the model is acceptable and can be used for design. After verifying the rutting prediction models of different pavement structures based on the RIOHTrack measured results, the predicted value of only the rutting with Structure I is close to the measured value. The R^2 of the rutting model can reach 0.60 and above, and the accuracy of other structures cannot reach the value. The reason for this phenomenon is that, on the one hand, the structure and material characteristics of some sections, such as rigid base structure and full-depth asphalt concrete layer structure, are not considered when the model is established, which leads to the poor prediction effect of the model on these structures. On the other hand, the RIOHTrack, which provides the measured data in this research, has certain differences from the model in climate and traffic environments. The rutting model can only be used with local correction.

At present, in terms of the rutting model, the commonly used correction method aims to introduce a local correction coefficient based on the existing model expression to improve the model, thereby improving the prediction accuracy. In [26–33], the local correction is carried out for the rutting model in MEPDG. The main method is that three local correction coefficients, namely, β_1, β_2, and β_3, are introduced to correct the constant term of the model, the exponential term of temperature, and the exponential term of cumulative ESALs, respectively. Subsequently, the model parameters are calibrated using the rutting observation results of local actual projects or test tracks. The rutting model in China's Specifications is similar to that in the MEPDG in its principles and expression. Therefore, this method can be used to make the local correction of the rutting model to establish a high-precision rutting model suitable for the region where the RIOHTrack is located. According to this idea, we propose a local correction method for the prediction model of the rutting performance of China's asphalt pavement, which is briefly described as follows:

(1) On the basis of the existing rutting performance prediction model Equation (3) in China, the local correction coefficients β_1, β_2, and β_3 are introduced to improve a new rutting prediction model; see Equation (7). Among them, β_1 is used to correct the constant term of the existing rutting model, β_2 is used to correct the exponential term of the temperature, and β_3 is used to correct the exponential term of the cumulative ESALs.
(2) Relying on local projects and test sections, long-term observation of rutting deformation of asphalt pavement is carried out, and the measured rutting data with the cumulative ESALs are obtained. These data can reflect the long-term evolution of pavement rutting under the combined effect of multiple factors such as local climate environment, traffic load, pavement structure, and material type.
(3) Based on the long-term observation results of rutting deformation, a new rutting prediction model after correction is used to fit the rutting data according to the least squares method, so the local correction coefficients β_1, β_2, and β_3 can be obtained, and the model prediction errors are obtained to judge the model accuracy. Finally, taking these coefficients into Equation (7), the new rutting prediction model after local correction can be obtained.

$$R_a = \sum_{i=1}^{n} 2.31 \times 10^{-8} \cdot \beta_1 k_{Ri} T_{pef}^{2.93 \cdot \beta_2} p_i^{1.80} N_e^{0.48 \cdot \beta_3} R_{0i} \quad (7)$$

Equation (7) is adopted to fit the measured results shown in Figure 6. The local correction coefficients of different structures and all kinds of errors in the model prediction can be obtained (Table 4). Table 4 shows that the accuracy of rutting prediction models of all structures is greatly improved after local correction. The determination coefficients R^2 are higher than 0.87, which indicates that the new rutting prediction model after local correction is suitable for the rutting prediction of all kinds of pavement structures where the RIOHTrack is located.

Table 4. Local correction coefficients and errors of rutting model.

Structure Type		β_1	β_2	β_3	MSE	RMSE	MAE	MAPE	R^2
I	STR1	6.1319	1.2123	0.5440	0.21	0.46	0.38	8.6%	0.9331
	STR2	6.1201	1.2120	0.5425	0.18	0.42	0.31	7.4%	0.9400
II	STR4	9.4764	1.2749	0.3677	0.11	0.33	0.24	6.6%	0.8722
	STR5	7.5312	1.2573	0.4409	0.13	0.36	0.26	6.4%	0.9237
III	STR7	7.0638	1.2254	0.5330	0.31	0.56	0.40	8.2%	0.9415
	STR8	5.4336	1.1970	0.6079	0.30	0.55	0.39	7.5%	0.9591
IV	STR10	7.2853	1.2287	0.5340	0.47	0.69	0.49	10.1%	0.9203
	STR12	10.0245	1.2674	0.4357	0.41	0.64	0.48	10.6%	0.8787
V	STR11	7.0344	1.2237	0.5301	0.34	0.59	0.46	8.7%	0.9311
	STR13	9.6484	1.2624	0.4367	0.31	0.56	0.42	9.2%	0.9045
VI	STR16	9.9075	1.2660	0.4412	0.31	0.55	0.39	10.0%	0.8901
	STR17	8.2984	1.2436	0.4598	0.24	0.49	0.38	9.6%	0.8913
VII	STR18	4.8346	1.1941	0.5643	0.46	0.68	0.52	10.8%	0.9312
	STR19	6.9198	1.2416	0.4625	0.25	0.50	0.37	7.9%	0.9073

Figure 7 shows the comparison of results before and after the local correction of the rutting models of several representative pavement structures. After local correction, the predicted values of the rutting models with these structures are relatively close to the measured values. The measured result fluctuates up and down near the prediction curve, the error of the model prediction decreases, and the accuracy is improved significantly. For Structures II and VII, the prediction curve is no longer above the measured curve but fluctuates up and down near the measured curve. R^2 becomes higher than 0.87 from a negative value. For STR5 with the smallest error, the MSE is 0.13 mm^2; the RMSE is 0.36 mm; the MAE is 0.26 mm; and the MAPE is 6.4%. The rutting model can fit the measured value of rutting better, and the prediction effect of the model is better. For Structures III, IV, V, and VI, the prediction curve is no longer parallel to the measured curve and no longer crosses in the middle but fluctuates up and down near the measured curve. R^2 increases to 0.87 and above from 0–0.50. For STR8 with the smallest error, the MSE is 0.30 mm^2; the RMSE is 0.55 mm; the MAE is 0.39 mm; and the MAPE is 7.5%. The accuracy of the model has been improved significantly.

Comparing the results in Figures 6 and 7, it can be seen that the prediction effect of the new rutting model after correction is significantly better than that of the model before, which is mainly related to the introduction of local correction coefficients β_1, β_2, and β_3. The evolution curves of the measured rutting values of 14 kinds of pavement structures in Figure 6 with the cumulative ESALs basically show a similar phenomenon; that is, the rutting deformation in the initial loading stage (N_e is about 0 to 5 million ESALs) increases rapidly, and the rutting evolution curve is relatively steep. When the initial stage is over, the rutting deformation begins to increase slowly, and the rutting evolution curve also becomes relatively flat. The reason for this phenomenon may be that in the initial loading stage, the voids inside the mixture of the newly paved asphalt pavement are compressed under the load, resulting in obvious compaction deformation of the asphalt concrete structure layer, as can be seen from Figure 6. At the end of the initial loading stage (generally N_e is about 5 million ESALs), the compaction deformation of the asphalt pavement can reach

about 4–6 mm. After that, due to the limited compressible voids inside the asphalt mixture, when the voids can no longer be compressed, the asphalt mixture begins to produce plastic permanent deformation. Compared with the compaction deformation, the increase of the plastic deformation is relatively slow and not as rapid as the compaction deformation in the initial stage.

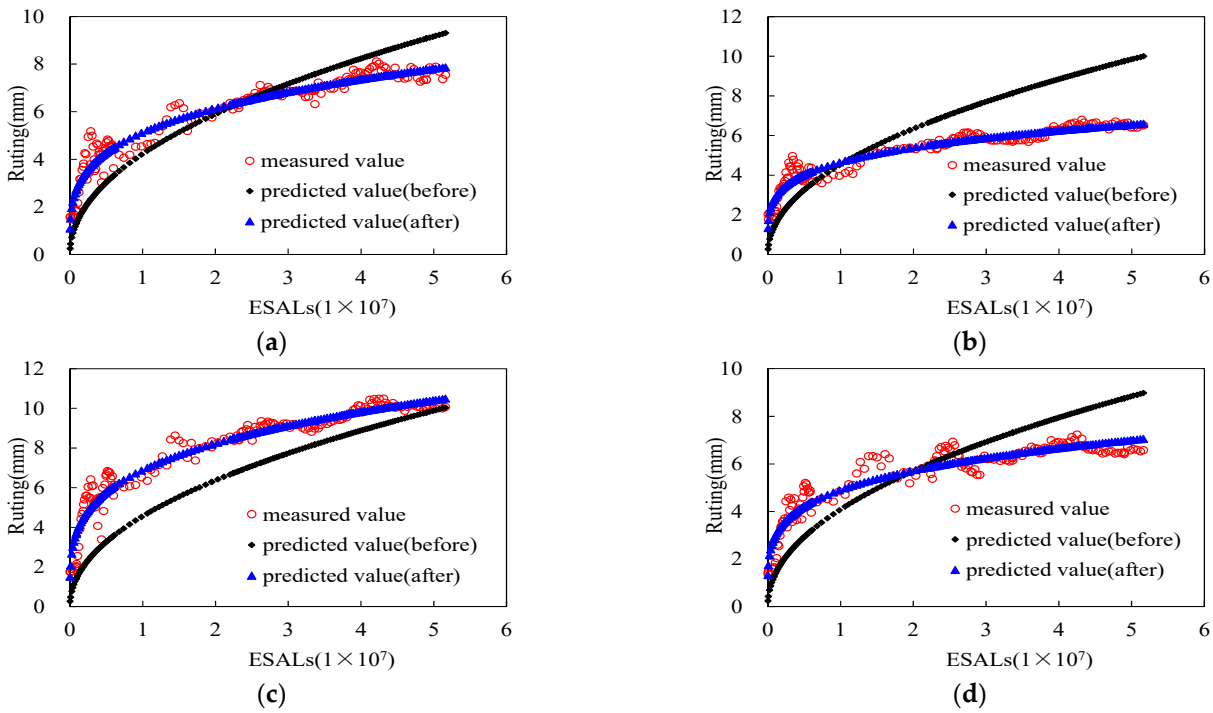

Figure 7. Comparison of predicted and measured values before and after rutting model correction. (**a**) STR2. (**b**) STR5. (**c**) STR7. (**d**) STR17.

As can be seen from Figure 7, although the overall change in trend of the new and old models is in the form of a monotonically increasing power function, the new model has a steeper curve shape in the initial loading stage, which can better simulate the initial compaction deformation of asphalt mixture when N_e is from 0 to 5 million ESALs. As seen in Equation (7), correction coefficients β_1 and β_2 respectively correct the constant term of the model and the exponential term of the equivalent temperature, and the equivalent temperature is fixed for the same structure, so the coefficient β_2 can also be regarded as a correction to the constant term. According to the results in Table 4, it can be seen that when correction coefficients β_1 and β_2 are introduced, the constant term of the new model is numerically at least approximately 6 times higher than that of the old model. In addition, when the initial loading stage is over, the evolution curve of the second stage of the new model is smoother than that of the old model, and it can better simulate the slowly increasing plastic permanent deformation, and the model prediction effect is also better. It can be seen from Equation (7) that β_3 mainly corrects the exponential term of N_e, and N_e is also the only independent variable in Equation (7), and the evolution curve in the second stage of the model mainly depends on the value of the exponential term. The smaller the value, the smoother the curve. From the values in Table 4, it can be seen that the average value of β_3 is about 0.5, the exponential term of the new model is half of that of the old model, and its curve is gentler, which can better simulate the slowly increasing plastic permanent deformation after the initial loading stage.

It should be noted that the measured rutting data of 14 kinds of structures in Figure 6 are obtained based on the accelerated loading test of the RIOHTrack's full-scale pavement structure. Since the test section is built in the wild, it has always been bearing the long-term effect of the local climate environment, and the pavement structure and material type are

quite different. In other words, the measured rutting data in Figure 6 is the test result under the combined effect of local climate environment, traffic load, pavement structure, and material type, which also comprehensively reflects the influence of these factors. On the basis of this test data, the new rutting prediction model obtained after local correction will have higher regional applicability, and is more suitable for rutting prediction of various pavement structures in the area where the RIOHTrack is located, and the accuracy is also higher.

7. Conclusions

Based on the measured value of the rutting model with the pavement structure represented by the RIOHTrack full-scale test track, the rutting prediction model in China's Specifications is analyzed. Moreover, the following conclusions are drawn:

(1) The rutting model in China's Specifications for Design of Highway Asphalt Pavement has significant structural dependence. Different structures are predicted using a unified rutting model with different prediction accuracies.
(2) The existing rutting model is used for prediction. Structure I has the highest accuracy and the smallest error, and the R^2 is greater than 0.6. Rigid base and full-depth asphalt pavement structures have the worst accuracy, and the R^2 is negative. The prediction accuracy of other structures is not high, and the R^2 is in the range of 0–0.5.
(3) To improve prediction accuracy, local correction coefficients are introduced in the existing rutting prediction model to establish a new one. The RIOHTrack rutting measured value is adopted to fit the new rutting prediction model, and the local correction coefficients of different structures are obtained.
(4) After local correction, the accuracy of the rutting prediction model of all structures is greatly improved. The R^2 values are greater than 0.87. The predicted values of the rutting models with these structures are relatively close to the measured values. The measured result fluctuates up and down near the prediction curve, the error of the model prediction declines, and the accuracy is improved significantly.
(5) The measured rutting data in this research are the test results under the combined effect of local climate environment, traffic load, pavement structure, and material type. On the basis of this test data, the new rutting prediction model obtained after local correction will also have higher regional applicability, and is more suitable for rutting prediction of various pavement structures in the area where the RIOHTrack is located, and the accuracy is also higher.

In this research, a local correction method of the rutting prediction model is proposed. Although this method is discussed for the rutting model in China's Specification, the basic principle of this method is to introduce correction coefficients. The constant terms, exponential terms of loads, and environment parameters in the model are modified respectively to improve the prediction accuracy of the model. The ideas and methods of this model correction also have a certain reference value for the correction of rutting models in other regions. When the accuracy of the estimation of the existing rutting models in other regions is poor, you can refer to this research's method to make local correction on key parameters to improve accuracy and enhance regional applicability. In addition, the RIOHTrack full-scale pavement test track, which this research is based on, is still carrying out accelerated loading tests. It is expected that by the end of 2022, cumulative ESALs will reach 65 million ESALs. The related work in this research will also carry out further tracking research and analysis with the update of long-term observation data of rutting.

Author Contributions: The authors confirm contribution to the paper as follows: conceptualization and methodology: X.Z.; data curation: Y.W. and Z.M.; formal analysis and validation: Y.W., X.Z. and X.W.; writing and visualization: Y.W., X.Z. and Z.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Key of Research and Development Plan under Grant number 2020YFA0714300.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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