

Enhancement of Accuracy of Tire Wear Prediction Method by Reflection of Material Temperature Characteristics

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ABSTRACT

In order to increase the prediction accuracy of tire wear, prediction error has been decreased by setting differing temperature characteristics for each rib in the tread rubber viscosity, characteristic of a prediction model. In addition, though previously challenging, calculation of the wear degree for each rib has increased the accuracy of uneven wear prediction, such as center wear in the front tires of front wheel drive vehicles and wear on the outer shoulders of rear tires. This prediction model will make it possible to predict the degree of wear, including uneven wear, from the initial stage of vehicle development in addition to studying rolling resistance and wet braking performances, which will contribute to increased vehicle development efficiency. By reducing the necessity of conducting wear evaluation tests using real vehicles, the model will also contribute to reducing the person-hours involved in testing.

1. Introduction

Automakers are reducing the rolling resistance of tires in order to increase fuel efficiency as a response to global environmental issues. Normally, when tread rubber with low hysteresis loss is employed to reduce tire rolling resistance, wet braking performance also declines. The use of silica as an additive in addition to conventional carbon black reduces hysteresis loss and boosts wet braking performance, but the wear life of the tire declines. It is necessary to balance these antagonistic tire performance demands with a combined variety of other design elements, such as the tire tread pattern, the internal structure of the tire, and the tire compound composition. These performance demands have a significant effect on vehicle performance design, and the ability to make accurate predictions at the initial stage of development would be a major contribution in raising the efficiency of the vehicle development process as a whole.

However, making predictions is not an easy task because wear life is affected by a large number of factors and design elements, including loads, slip velocity, the physical properties and temperature characteristics of the rubber used, road surfaces, and driving conditions. This means that

studies necessitate extended periods of driving tests, and this has a significant developmental effect.

Previously proposed methods of evaluating wear can be broadly divided into evaluation using driving tests, and evaluation on the bench.

In wear evaluation using driving tests, benchmark tires and the tires under evaluation are fitted to vehicles, allowing for conditions to be close to actual use environments. However, it is not easy to hold factors in the test environment constant, such as road surface conditions, vehicle operation, external temperatures, and sunshine. Relative wear evaluations are therefore mainly used in the later stages of vehicle development, and rarely applied in the initial stages.

Wear evaluation on the bench involves a combined evaluation of the form of wear, using a unit tire wear test apparatus, and the distribution of wear energy on the surface of the rolling tire, using a wear energy test apparatus^{(1), (2)}. These evaluation methods make it possible to hold the test environment constant, and because they do not use an actual vehicle, they can be readily employed for studies in the initial stage of development. However, the test apparatus road surface differs from an actual road. In the case of a drum test apparatus, the shortening of

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the tire's contact patch length produces differences in the condition of the tire contact patch, and at times it is not possible to reproduce wear in actual use environments. Kobayashi, et al proposed a prediction method based on Scallamach's theory, combining wear energy with an index expressing the wear resistance of the rubber⁽³⁾. Excepting the shoulders of the tire, the predictions made using this method corresponded well with data from actual use environments.

In a previous paper⁽⁴⁾, the authors proposed a prediction model based on a wear volume formula for polymer abrasion⁽⁵⁾, using the physical properties of tread rubber and contact patch data to accurately predict the wear life of the front wheels on a front wheel drive (FF) vehicle. However, issues remained in relation to the prediction of uneven wear of the front tires and the accuracy of prediction of wear life in the rear tires.

This paper discusses the correction of this prediction model to make it possible to reflect different temperature characteristics for each rib in the tread rubber viscosity characteristic employed in the new model, based on the finding of Hirayama, et al⁽⁶⁾, that the wear life of tire tread rubber displays a strong correlation with the properties of the rubber at lower temperatures, rather than road surface temperatures. It was verified that the prediction of wear life using the new model, including wear in the rear tires and uneven wear, displayed sufficient accuracy for use in vehicle development.

2. Tire Wear Life Prediction Formula

The authors' previous paper proposed a model for the prediction of tire wear life employing a wear volume formula for polymer abrasion (Eq. (1) below).

$$V = k \frac{\mu WL}{H\sigma\varepsilon} \quad (1)$$

V : Wear volume [mm³]
 k : Constant [-]
 μ : Coefficient of friction [-]
 W : Load [N]
 L : Slip distance [mm]
 H : Rubber hardness [°]
 σ : Breaking strength [MPa]
 ε : Breaking strain [%]

This model expressed the wear life of groove i , shown in Fig. 1, L_{ti} , as Eq. (2), using wear speed for each rib, V'_j ,

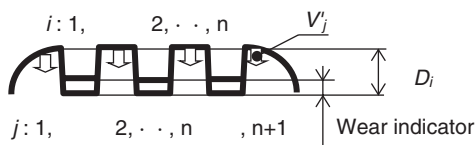


Fig. 1 Tread rib wear speed and groove depth

the groove depth at i , D_i , and a wear indicator height of 1.6 mm.

$$L_{ti} = \frac{2 \times (D_i - 1.6)}{V'_j + V'_{j+1}} \quad (2)$$

L_{ti} : Wear life [km]
 i : Groove position No.
 j : Rib position No.
 D_i : Groove depth at i [mm]
 V'_j : Wear speed at j [mm/km]

The wear coefficient in Eq. (1), μ , can be expressed as a function of the storage elastic modulus, E' , and $\tan \delta$, which both display temperature characteristics. In this paper, μ is expanded with consideration of the temperature characteristic as shown in Eq. (3), based on findings reported in a paper by Kawakami, et al⁽⁷⁾.

$$\mu(T) = f[\tan \delta(T), E'(T)] \quad (3)$$

$\mu(T)$: Coefficient of friction at T (°C) [-]
 T : Temperature [°C]
 $\tan \delta(T)$: Loss factor at T (°C) [-]
 $E'(T)$: Storage modulus at T (°C) [-]

The distribution of both contact patch stress and tire surface temperature in a tire fitted to an actual vehicle, is affected by tire deformation and the heat generated by friction with the road surface. Due to this, wear in each rib is dependent on the shape of the contact patch, as well as alignment factors such as toe and camber, and can therefore be considered to differ for each rib. The wear volume formula for each rib, Eq. (4), can therefore be defined by substituting μ in Eq. (1) with the coefficient of friction in Eq. (3), $\mu(T)$.

$$V_j = k_j \frac{\mu_j(T) W_j L_j}{H\sigma\varepsilon} \quad (4)$$

V_j : Wear volume at j [mm³]
 k_j : Constant at j [-]
 $\mu_j(T)$: Coefficient of friction at j [-]
 W_j : Contact patch pressure at j [MPa]
 L_j : Slip distance at j [mm]

This makes it possible to express the wear speed for each rib, V'_j , as Eq. (5).

$$V'_j = k_j f(W_{aj}, W_{bj}, S_j, E'_j(T), \tan \delta(T), H, \sigma, \varepsilon) \quad (5)$$

W_{aj} : Average pressure [kg/mm²]
 W_{bj} : Maximum pressure [kg/mm²]
 S_j : Slip distance (calculation) [mm]

As H , σ , and ε in Eq. (4) are materials terms, in this paper they are considered constant, irrespective of the rib position. In addition, because the load term, W , and the slip

distance term, L , are affected by alignment, W_j and L_j have been employed.

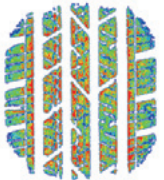
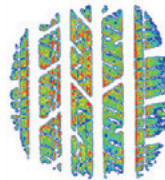
3. Tire Contact Patch

W_j , L_j , and $\mu_j(T)$ in Eq. (4) are determined for each rib in order to reflect the differences in the mechanism of wear for each rib in the contact patch and the differing wear conditions for the front and rear tires in the prediction model.

In most cases, the front tires on an FF vehicle tend to display center wear due to acceleration and deceleration, while rear tires tend to display shoulder wear as a result of initial alignment. It can therefore be hypothesized that differences in the stress distribution and heat balance of the contact patch affect wear life. Contact patch pressure was measured for front and rear tires in order to verify this hypothesis. The distribution of shear force in the contact patch during acceleration and deceleration, a factor in center wear in front tires, was also measured. In the case of the shoulder wear in rear tires, toe and camber angles were imparted to tires, and the temperature of the contact patch when the tire was rolling was measured, and the distribution of wear energy in the contact patch was studied.

3.1. Contact Patch Pressure for Each Rib

Contact patch pressure was measured and the load term, W , was determined in order to study the effect of load on the front and rear tires, as well as their toe and camber angles on the load on each rib. Figure 2 shows a sample of the measurement results (215/50R16 100S). The figure shows measured values for average contact patch pressure, W_a , maximum contact patch pressure, W_b , and the ratio of W_a and W_b for each rib when the center rib contact patch pressure is 1.

	Front					Rear				
Foot print										
Rib No.	#1 (out)	#2	#3*	#4	#5 (in)	#1 (out)	#2	#3*	#4	#5 (in)
Load [kN]	4.82					3.55				
Toe [°]	0					0.09 (in)				
Camber [°]	0					1.00 (negative)				
W_a [MPa] (%)	0.36 (94)	0.36 (96)	0.38 (100)	0.37 (98)	0.36 (94)	0.37 (97)	0.36 (95)	0.38 (100)	0.37 (97)	0.36 (95)
W_b [MPa] (%)	1.44 (160)	1.10 (122)	0.90 (100)	0.93 (103)	1.44 (160)	1.43 (130)	0.90 (82)	1.10 (100)	1.19 (108)	1.43 (130)

* Reference for maximum and average pressure

Fig. 2 Maximum and average pressure of contact patch

Table 1 Calculation results for slip distance

	Front					Rear				
Rib No.	#1 (out)	#2	#3	#4	#5 (in)	#1 (out)	#2	#3	#4	#5 (in)
Slip distance [mm]	4.43	5.26	5.49	5.22	4.61	10.14	7.21	4.13	0.74	3.03

Figure 2 shows that W_a is highest for the center of the tire and W_b is highest for the shoulders of the tire for both front and rear tires. In addition, it was considered that due to factors such as the load on the front and rear tires, as well as differences in alignment, the effect of W on wear differs for each rib. It was further considered that the accuracy of wear prediction could be increased by setting W_a and W_b for each rib.

3.2. Calculated Values of Slip Distance for Each Rib

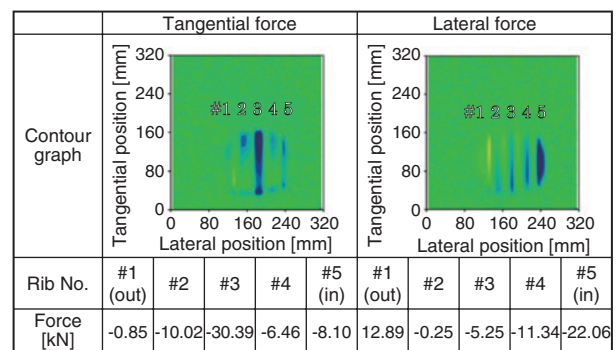
Because it is not easy to directly measure the slip distance term, L , as in the authors' previous paper, this term was calculated for each rib using a geometrical method. Table 1 shows the calculation results.

The results in Table 1 show that for the front tires, the slip distance tends to become higher the closer the rib is to the center of the tire, while in the rear tires, slip distance tends to become higher the closer the rib is to the outer side of the tire. This matches the tendency of the front tires to display center wear and the rear tires to display shoulder wear.

3.3. Factor Analysis of Tire Wear

A force matrix sensor manufactured by A&D Company, Limited, was employed to measure the shear force of the contact patch in front tires while fitted to a vehicle and rolling. Figures 3 and 4 respectively show an example of the results for acceleration and deceleration.

The measurement results shown in Figs. 3 and 4 indicate that a large shear force is produced on the center rib during acceleration and that shear force is distributed



Load: 4.3 [kN] Temperature: 25 [°C] V = 34.3 [km/h]

Fig. 3 Contact patch shear force during vehicle acceleration

uniformly on each rib during deceleration.

These results conform with the tendency of the calculation results for slip distance shown in Table 1, and also match the empirical observation that the front tires in FF vehicles display center wear.

Next, the temperature of the surface of the tire tread when rolling was measured using a flat-belt tire-test machine in order to determine the effect of the rear tire toe and camber angles on the contact patch's temperature. Figure 5 shows temperature measurement results for each rib, and Fig. 6 shows measurement results for the temperature distribution in the tread cross-section.

The results shown in Fig. 5 indicate that the temperature of the outer rib is 1.9°C lower than the temperature of the inner rib.

The results in Fig. 6 show that temperature is lower on the outer side of the tire for the entire tread cross-section as well.

The energy budget of the tire surface is a balance between dynamic energy generated by the deformation of the rubber due to slip and heat energy generated by internal hysteresis⁽⁸⁾, as shown in Eq. (6), and the amount

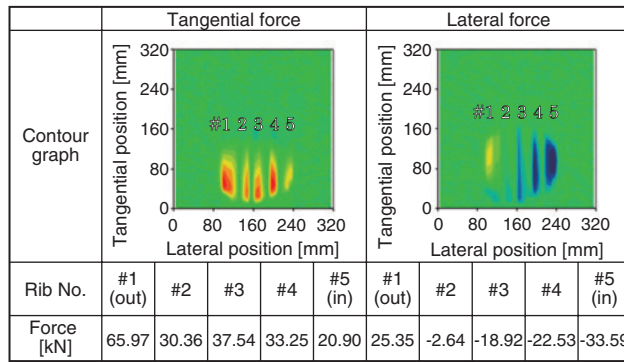


Fig. 4 Contact patch shear force during vehicle deceleration

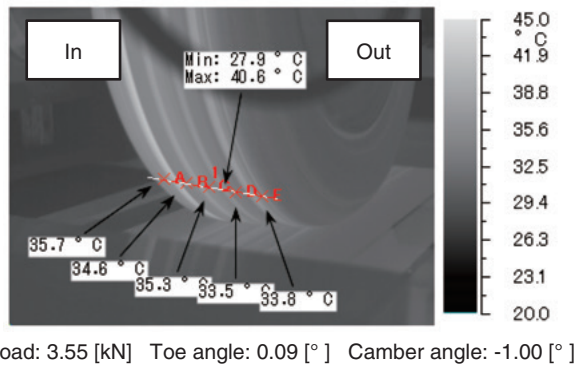


Fig. 5 Measurement of tire surface temperature on flat track

of energy that is dissipated. It is considered that because of this, internal heat generation is controlled and the surface temperature is lower in sections of the tire with a high-slip distance.

In addition, wear advances more rapidly the lower the temperature of the tire tread rubber is. Due to this, wear is swifter to appear in the outer section of the tire, where slip distance is high and temperature is low. These results indicated that it would be possible to realize a more accurate wear prediction by employing the proposed method and using a temperature-dependent coefficient as the $\mu(T)$ term for each rib.

$$W_l = \int_0^{\frac{2\pi}{\omega}} \sigma \dot{\epsilon} dt = \pi \epsilon_0^2 E'' = \pi \epsilon_0^2 E' \tan \delta \quad (6)$$

W_l : Strain energy [J]

σ : Internal stress [MPa]

ϵ : Strain [mm]

ϵ_0 : Maximum strain [mm]

3.4. Calculation of Wear Prediction Model Coefficients

In their previous paper, the authors used the value at $T = 25$ [°C] for the $\mu_j(T)$ term in Eq. (4). In this paper, experimentally determined optimal values will be employed for each rib. Wear speed in Eq. (2), V_j is calculated using Eq. (7).

$$\log V_j' = C_{waj} \times W_{aj} + C_{wbj} \times W_{bj} + C_{sj} \times S_j + C_{s2j} \times S_j^2 + C_{c(E')j} \times E_j'(T) + C_{c(\tan\delta)j} \times \tan\delta(T) + C_{c(H)j} \times H + C_{c(\sigma)j} \times \sigma + C_{c(\epsilon)j} \times \epsilon + k_j \quad (7)$$

C_{waj} : Coefficient of average pressure

C_{wbj} : Coefficient of maximum pressure

C_{sj} : Coefficient of slip distance

C_{s2j} : Coefficient of slip distance (square member)

$C_{c(E')j}, C_{c(\tan\delta)j}, C_{c(H)j}, C_{c(\sigma)j}, C_{c(\epsilon)j}$: Coefficient of rubber

In order to calculate optimal values, $\tan \delta$ and E' for each rib of the front and rear tires were varied within a range

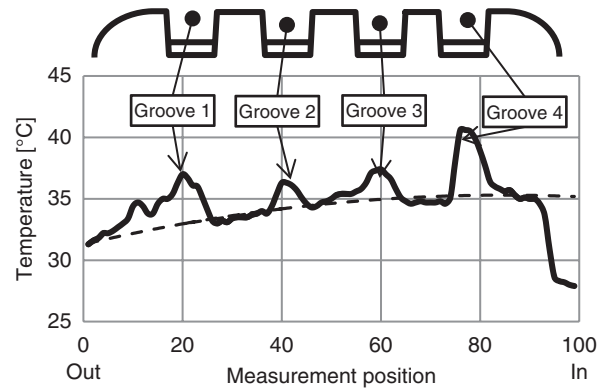


Fig. 6 Tire surface temperature distribution on flat track

Table 2 Maximum correlation coefficient and temperature

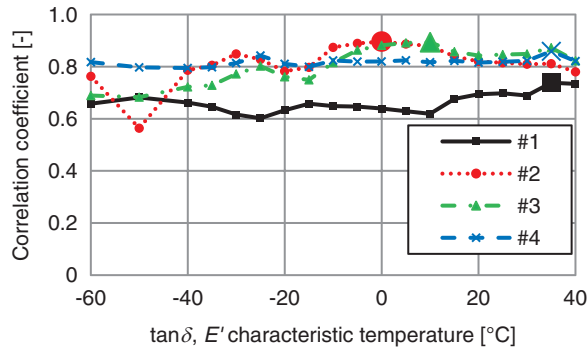
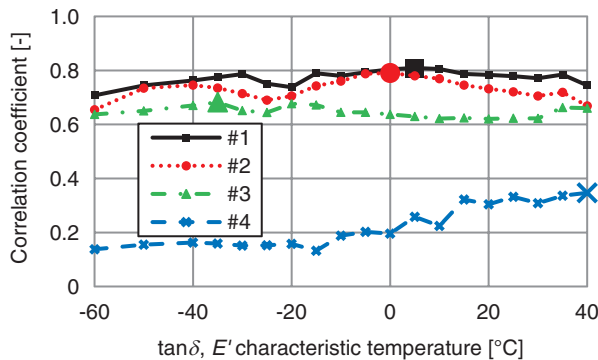
Groove position			#1 (out)	#2	#3	#4 (in)
Correlation coefficient [-] at temperature [°C]	Front	Current	0.766 (at 25)	0.802 (at 25)	0.800 (at 25)	0.844 (at 25)
		Proposed	0.738 (at 35)	0.896 (at 0)	0.893 (at 10)	0.859 (at 35)
	Rear	Current	0.793 (at 25)	0.311 (at 25)	0.403 (at 25)	0.145 (at 25)
		Proposed	0.809 (at 5)	0.791 (at 0)	0.683 (at -35)	0.347 (at 40)

between -60°C and 40°C , and a multiple regression analysis was conducted. The temperatures at which the correlation coefficients, between the results of predictions using the model and the results of driving tests for $\tan\delta$ and E' , were at their highest were determined by this analysis. Figures 7 and 8 show graphs of the temperatures for $\tan\delta$ and E' employed in calculations and the correlation coefficients, while Table 2 shows the maximum correlation coefficients and the temperature at that time.

Table 3 shows the coefficients employed in Eq. (8), obtained from Table 2. Using these it was possible to set wear speed formulas for each rib.

Table 3 Results for multiple regression model coefficients

Groove position		Front				Rear			
		$i=1$ (out)	2	3	4 (in)	$i=1$ (out)	2	3	4 (in)
Load factor (Ave.)	W_a	0.20	-0.05	-0.05	-0.25	-0.38	-0.64	-0.63	-0.21
Load factor (Max)	W_b	0.06	-0.02	-0.02	0.02	0.04	-0.05	-0.06	-0.04
Slip distance	S	8.51	6.12	6.12	-2.23	1.78	1.33	1.17	-2.03
Slip distance (Square)	S^2	-7.22	-4.67	-4.67	12.59	-0.80	-0.97	-0.83	1.57
Material property	C_c ($\tan\delta$)	0.00	-0.35	-0.35	0.01	-0.30	-0.13	0.10	0.22
	C_c (H)	0.62	-0.25	-0.25	-0.94	-0.63	-0.15	-0.14	-0.15
	C_c (ε)	0.33	-0.20	-0.20	-0.52	-0.15	-0.04	-0.06	0.07
	C_c (σ)	-0.21	1.02	1.02	0.61	0.50	0.39	0.48	-0.16
	C_c (E')	-2.02	0.66	0.66	2.73	0.63	0.05	0.00	-0.79
Constant	k	-3.93	1.92	1.92	6.22	5.43	4.50	3.47	4.04

Fig. 7 Relationship between $\tan\delta$, E' and correlation coefficient for front tireFig. 8 Relationship between $\tan\delta$, E' and correlation coefficient for rear tire

4. Accuracy Verification

In order to verify the accuracy of the proposed tire wear prediction model, passenger vehicles in categories B to D, and SUV, were employed to conduct driving tests of 15 types of tires, and the accuracy of predictions made using the models proposed in the authors' previous paper, and those models proposed in this paper, were then compared.

4.1. Results of Wear Life Prediction

Tables 4 and 5 show wear life measured in driving tests and wear life predicted using the current and proposed models for the front and rear tires.

Using these results, the predictive accuracy of each model in relation to wear life in driving tests was studied. Figures 9 and 10 respectively show results for the front tires and the rear tires.

As Fig. 9 shows, the average error of values estimated using the prediction model in relation to the results of front tire wear tests using actual vehicles was 15.7% for the previous model, but 12.5% for the proposed model, representing a 3.2-point reduction in error. In the case of the rear tires, a 2.4-point reduction was realized, from 16.2% to 13.8%, as shown in Fig. 10.

The correlation coefficients between wear life measured in driving tests and wear life predicted by each model were also studied. Figure 11 shows results for the front tires, and

Table 4 Front tire wear life

	Wear life [1000 km]														
Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Measurement	34.1	30.3	29.2	32.3	33.2	36.8	34.7	31.1	25.6	28.2	28.5	23.0	21.1	20.8	20.8
Current	32.4	35.1	29.8	37.3	39.7	37.1	32.9	32.9	33.3	32.7	30.6	29.9	24.9	24.6	27.1
Proposed	31.4	35.1	29.9	33.3	36.7	36.5	34.1	34.0	32.0	30.7	30.1	26.7	25.9	25.1	28.6

Table 5 Rear tire wear life

	Wear life [1000 km]														
Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Measurement	58.9	77.6	54.9	85.2	47.3	75.2	52.0	45.2	54.5	47.7	40.1	40.3	57.6	45.9	35.7
Current	44.1	67.2	49.3	73.8	53.1	68.5	49.3	53.1	68.7	54.1	46.1	51.1	49.0	39.8	46.6
Proposed	46.3	72.3	46.2	67.8	52.8	65.3	48.4	46.8	67.4	45.7	45.7	47.8	53.3	40.6	45.4

Fig. 12 shows results for the rear tires.

The correlation coefficient for the front tires has increased from 0.821 to 0.866, and the correlation coefficient for the rear tires has increased from 0.760 to 0.809.

This verifies that consideration of the temperature characteristic of the tires has increased the accuracy of prediction. It is considered that the application of this prediction model in the tire development process for new vehicles will reduce the need for tire verification tests in the case of tires for which the previously reported model was

not able to determine whether an actual vehicle verification test was necessary or not.

4.2. Results of Uneven Wear Prediction

As Table 2 showed, consideration of the temperature characteristic in relation to μ made it possible to increase the correlation coefficients for grooves #2 through #4 for the front and rear tires.

It was considered that this would increase the accuracy of uneven wear prediction, and the results of driving tests and wear life predictions using each of the models were therefore compared for each groove in the front and rear tires. Figure 13 shows the results of Test No. 10, as an example of the results.

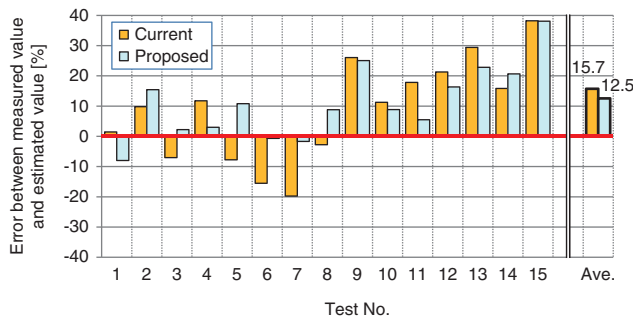


Fig. 9 Accuracy of prediction of front tire wear life for current and proposed method

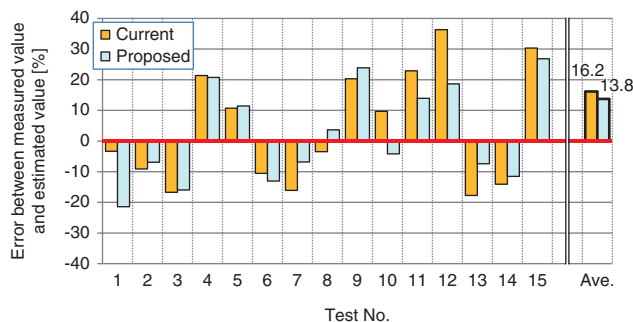


Fig. 10 Accuracy of prediction of rear tire wear life for current and proposed method

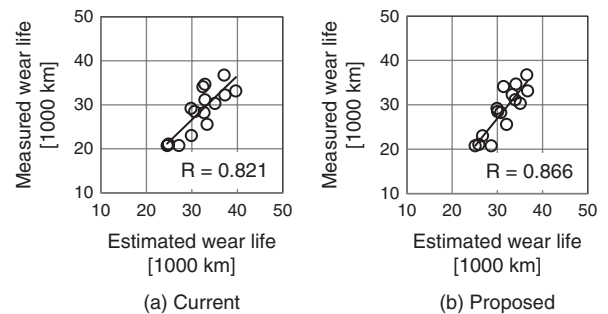


Fig. 11 Estimation and measurement of front tire wear life

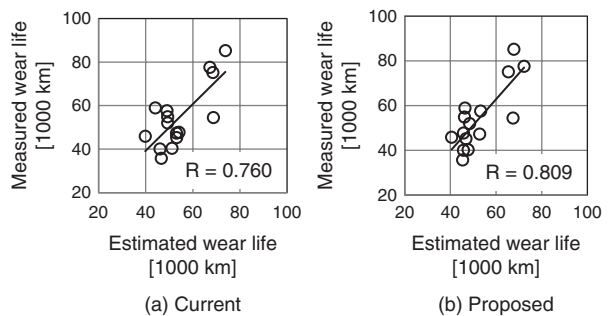


Fig. 12 Estimation and measurement of rear tire wear life

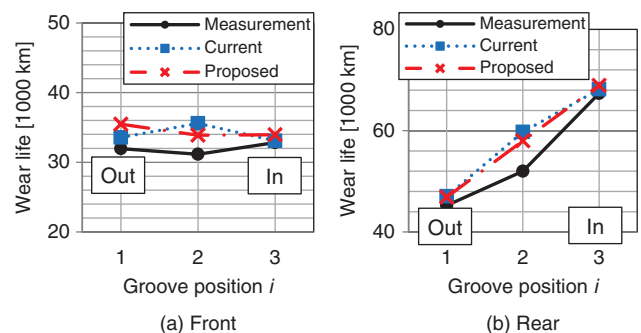


Fig. 13 Estimation and measurement of uneven wear

The use of the proposed model made it possible to predict the tendency of center wear for the front tires, which was calculated as shoulder wear inaccurately using the previous model. With regard to wear in the rear tires, the model was also able to accurately predict the tendency of wear in the shoulders of the tire, and the values predicted for wear in each groove were close to the results of driving tests. These results indicated that the proposed model increased the prediction accuracy of uneven wear.

5. Conclusion

A method of increasing the accuracy of a tire wear life prediction model was proposed, and its effectiveness was studied.

It was verified that taking the differing temperature characteristics of each rib from the front and rear tires into consideration for the wear coefficient, μ , employed in the wear life prediction model increased the accuracy of wear prediction and also increased the correlation coefficient between the results of predictions and driving tests. In addition, the accuracy of prediction of uneven wear was also increased. These results demonstrated that the proposed model was able to predict wear including differences in the form of uneven wear.

The application of this model in the new tire development process will make it possible to study performance during the initial stages of vehicle development, contributing to increased development efficiency. In addition, by reducing the necessity for wear evaluations in driving tests involving actual vehicles, the application of the model will also contribute to reducing the development time period.

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References

- (1) Sakai, H.: Study on the Wear of Tire Tread Rubber Part 2. Friction and Wear Under Condition of Large Slip Velocity, *Journal of the Society of Rubber Science and Technology*, Japan, Vol. 68, No. 4, p. 251-257, (1995) (in Japanese)
- (2) Yamazaki, S., Suzuki, T., Fujikawa, T.: Analysis of Influence of Drum Curvature on Tire Tread Wear in Indoor Wear Test, *Journal of the Society of Rubber Science and Technology*, Japan, Vol. 70, No. 7, p. 392-398, (1997) (in Japanese)
- (3) Kobayashi, H., Haraguchi, T., Kato, K.: Estimation Method of Tire Tread Wear Life, *TOYOTA Technical Review*, Vol. 50, No. 1, p. 50-55, (2000)
- (4) Tsutsumi, S., Ando, T., Nohtomi, S., Mizone, T.: An

Investigation of Tire Wear Life Prediction Method using Abrasive Wear Volume Formula, *JSAE Annual Congress Proceedings*, No. 1-176, p. 1979-1984, (2016) (in Japanese)

- (5) Ratner, S. B., Farberova, I. J., Radybeovich, O. V., Luré E. G.: *Abrasion of Rubber*, James, D. I. Ed., MacLaren, London, p. 145, (1967)
- (6) Hirayama, M., Nishino, T.: Scaling of Wear Resistance of Rubber Compounds for Tires Using Rubber Properties, *Journal of the Society of Rubber Science and Technology*, Japan, Vol. 86, No. 1, p. 3-7, (2013) (in Japanese)
- (7) Kawakami, S., Hirakawa, H., Misawa, M.: Interpretation of Wet Friction Coefficient by the Viscoelastic Nature of Rubber, *Journal of the Society of Rubber Science and Technology*, Japan, Vol. 61, No. 10, p. 722-727, (1988) (in Japanese)
- (8) Bridgestone Co.: *Jidoushayou Taiya no Kiso to Jissai*, Tokyo Denki University Press, p. 238, (2008) (in Japanese)

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