

“Statistical Tire Model” Identified from Data Group of Multiple Tires

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ABSTRACT

A statistical tire model has been developed. This tire simulation model is for use in the feasibility study of performance design at the initial stage of vehicle development. Using this method, existing data sets for the performance and characteristics of multiple tires are statistically modeled. The model is available to estimate values for tire performance and characteristics based on the input values for specifications such as tire size. By contrast with conventional tire models, the statistical tire model is able to estimate the characteristics of multiple tires of differing sizes and specifications using a single model without the measurement and modeling of data for each single tire.

1. Introduction

1.1. Background

The process of setting performance targets at the initial stage of vehicle development is termed performance design. Today, with the greater proportion of CAE in use in vehicle development, it is becoming increasingly important to conduct performance design at the beginning of the development process systematically and with a high degree of accuracy.

The tires are an important element in performance design, having a significant impact on many aspects of the performance and commercial appeal of the completed vehicle, including the chassis layout, handling performance, vehicle stability, brake performance, ride comfort, quietness and fuel efficiency. The multiple characteristics demanded from tires exert a mutual effect on each other, and are sometimes antagonistic. Because of this, it is necessary to realize a more accurate balance between these characteristics.

In addition, major changes in the size of the tires during the development process can have a significant effect on the chassis layout and the overall performance of the vehicle, and it is therefore desirable to decide on the specifications of the tires based on sufficiently accurate and broad-ranging studies at the initial stage of the development process.

1.2. Conventional Tire Model Approach

A variety of tire models are employed in performance design, including experimental models, theoretical models, and finite element models (FEM), a type of theoretical model (Table 1).

Table 1 Tire models for vehicle dynamics simulation

Model type	Application	Tire size effect simulation	Source data	Arbitrary tire size characteristic estimation
Experimental model	Statistical model	Single model for any size	Multi-tire data group	Available
	Magic Formula, etc.	Separate model for each size	Single tire data	Not available
Theoretical model	Brush model SWIFT, FTire etc.	Separate model for each size	Single tire data	Not available
	FEM model	Separate model for each size	Single tire data	Not available

Experimental models are produced by curve-fitting test data using approximation equations. The Magic Formula tire model is a standard example of an experimental model, widely used in applications including mechanism analysis and driving performance simulations. Standard examples of theoretical models include SWIFT and FTire. In theoretical models, the physical phenomena associated with the tires are expressed using theoretical expressions. These models frequently employ empirical formulas and constants obtained by experiment in specific sections. In the case of FEM models, characteristics are determined using CAD models of detailed structures. In many cases, data obtained from tests on actual tires are used in the verification and correlation of the models^{(1), (2)}.

Irrespective of the type of model used, it is standard procedure to model the various characteristics based on test data obtained separately for various conditions, such as tire sizes, inflation pressures, and loads. When these models are used in the performance design of parameters such as

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handling performance and vehicle stability at the initial stage of vehicle design, and tire size and use conditions are changed in studies of performance, it is necessary to utilize models identified for each respective set of conditions. However, in actual practice it is challenging to prepare tire models for all sizes and conditions in advance, and in addition there are also cases in which tire sizes for which no previous data exists are used, and it is necessary to study vehicle performance on the basis of predictions.

To respond to these issues, for the performance parameters of the greatest importance, in addition to conducting test measurements and modeling the tires, designers substitute tire models with similar characteristics and correct similar models based on estimates. However, in order to increase the precision and efficiency of performance design and expand the scope of comparative study, tire models able to estimate the characteristics of tires of various sizes and specifications without the necessity for measurement and modeling of individual tires are necessary.

2. Overview of Development of New Tire Model

2.1. Concept

In order to resolve the issues discussed above, it would be necessary to be able to estimate the characteristics of tires of varying sizes under varying conditions using a single model. It was considered that a tire model capable of estimating the characteristics of tires of differing sizes and specifications could be obtained by expanding an experimental model identified from data for a single tire into a model identified from a data group encompassing tires of multiple sizes and types (Fig. 1).

2.2. Method of Statistical Modeling

In order to realize a model of this type, a system identification method was used to formulate a single multi-dimensional approximation equation model from a data group encompassing tires of multiple sizes and specifications. System identification is a form of

statistical identification that takes into consideration the conformity to physical laws of system characteristics between input (explanatory variables) and output (objective variables)⁽³⁾. The flow of the procedure is as follows (Fig. 2):

- (1) Projection of model equations based on prior information (existing knowledge);
- (2) Identification of approximation equation constants using test data;
- (3) Verification of accuracy of model by evaluation of error;
- (4) Repeated correction of model until adequate accuracy is obtained; and
- (5) Determination of model by introduction of constants to approximation equations.

This method is widely employed in all modeling. From the perspective of the fact that it models the relationship between input and output using approximation equations, the method is the same as that employed in creating a single-tire experimental model. However, it differs in the fact that it identifies a single model from a data group for multiple tires of differing sizes. This means that it is possible to estimate tire characteristics by employing variables related to sizes and specifications, which are not normally incorporated in a single-tire model, as input (Fig. 3).

The application of this method to existing, previously accumulated data groups makes it possible to obtain models

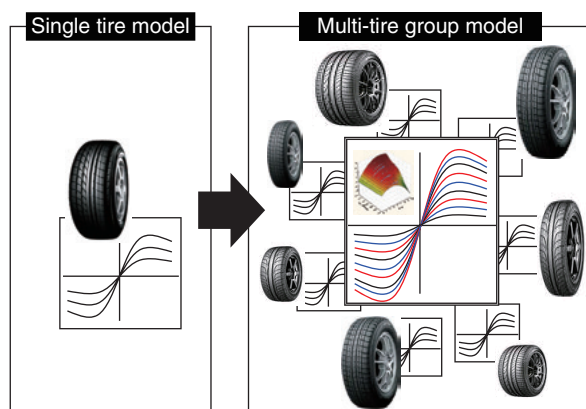


Fig. 1 New tire model from tire data group

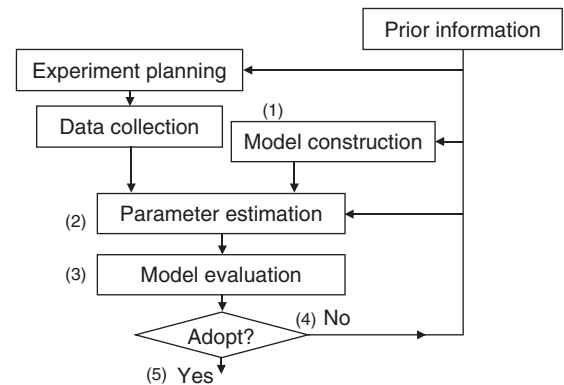


Fig. 2 System identification flow chart

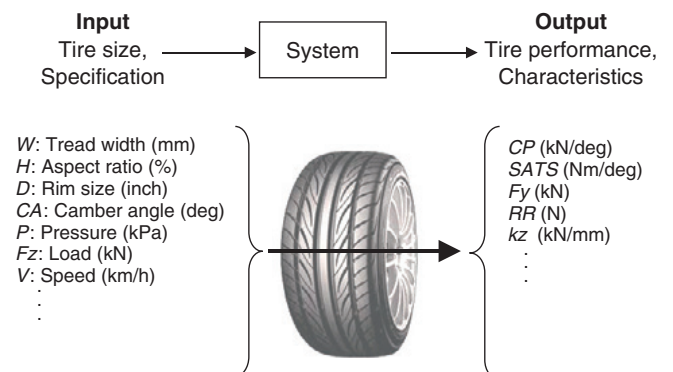


Fig. 3 System identification parameters

able to estimate the characteristics of tires of varying sizes and specifications.

Research has proceeded towards the application of tire models of this type, termed “statistical tire models.” To date, research has been conducted on the modeling of tire characteristics including cornering power, CP ; vertical spring stiffness, k_z ; self-aligning stiffness, $SATS$; side force characteristic, F_y ; and rolling resistance, RR , using this method, and the application of the method to the statistical generation of Magic Formula models. This paper will provide an overview of this research, with a focus on statistical CP models as a representative example of its application.

3. Statistical CP Models

3.1. Benefit of Statistical CP Models

Tire CP expresses the side force generated per unit angle of the tire’s side-slip angle, and is an important tire characteristic, affecting parameters such as handling performance and vehicle stability. The load-dependence of CP expresses the characteristic of change in CP in relation to vertical load, F_z . This is an important characteristic because it changes the ratio of front-rear tire force in response to the front-rear distribution of load, and has a significant effect on the steering characteristic of the vehicle.

Tire size has a strong effect on the tire’s CP characteristic, and is a factor that affects elements of performance including handling performance and vehicle stability. Because of this, it is important to examine it quantitatively at the initial stage of performance design. In addition, tire size also affects numerous other vehicle characteristics including brake performance, ride comfort, fuel efficiency, and quietness, and it is necessary to also take these characteristics into consideration when studies are conducted.

Given the above, in order to study vehicle dynamic performance, it is essential to estimate the CP characteristic for tires of diverse sizes and to conduct computational studies. Using a statistical CP model capable of estimating CP when tire size is given, it would be possible to efficiently study the tire size necessary for realizing target vehicle performance at the initial stage of performance design.

3.2. Formulation of Statistical CP Model

In order to clarify the relationship between tire CP and the basic tire characteristics width, W ; profile, H ; wheel diameter, D ; inflation pressure, P ; and vertical load, F_z , single-dimensional regression analyses were conducted for test data for approximately 130 types of tires. The results are shown in Figs. 4 and 5.

As is generally known, CP tends to increase when the width of tires is increased, their profile is reduced, and their diameter is enlarged. The results show that this tendency is

basically linear (Fig. 4).

In addition, it can be observed from Fig. 5 that CP behaves as a quadratic function in relation to F_z , and becomes saturated at high loads.

As this indicates, the general characteristics of tires appeared in a single-regression analysis, but the gap between regression lines or curves and test data was too great for the estimation of CP from tire size during initial performance studies, and the level of accuracy could not be considered sufficient. The change in CP in relation to F_z and W was therefore observed in order to investigate the multiple correlations between variables. Figure 6 shows an example of the results.

Figure 6 indicates that the increase in CP close to zero

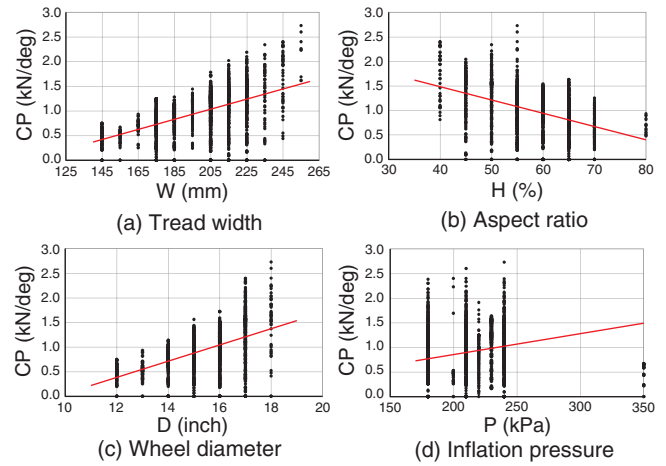


Fig. 4 CP relation to tire size parameters

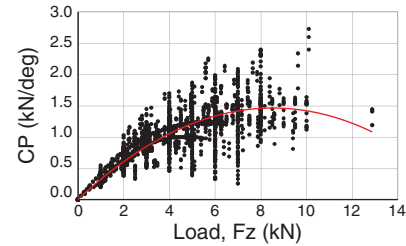


Fig. 5 CP relation to tire load, F_z

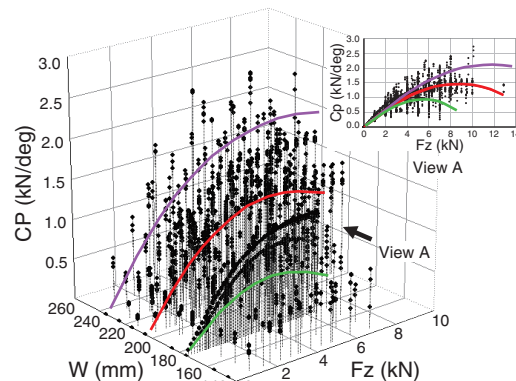


Fig. 6 CP relation to both F_z and W

load becomes steeper the wider the tire is made, and the load at which CP becomes saturated also shifts to the high-load side. This suggests that the second-degree behavior of CP in relation to Fz represents functions for parameters such as tire width, W .

Figure 7 shows the results of plotting test data for CP against Fz , W , H , D , and P , respectively, and approximating for smooth curved surface functions. The obtained approximated curved surfaces described quadratic function curves in relation to Fz , and their curvature and peak positions had all been transformed to basically linear functions in relation to W , H , D , and P .

Based on the above considerations, the function expression for the multi-dimensional regression of CP was hypothesized as shown below. If CP is approximated by a quadratic function of Fz , its curvature is termed A , and Fz that imparts the maximum value is termed B , CP is expressed by Eq. (1a). If it is assumed that $CP=0$ when $Fz=0$, the approximation function of CP is expressed by Eq. (1b).

$$CP = A(Fz - B)^2 + C \quad (1a)$$

$$CP = A(Fz^2 - 2BFz) \quad (1b)$$

The variables are substituted as follows.

$$A = \alpha$$

$$-2AB = \beta$$

The multi-dimensional regression model of CP in which curvature and peak position are transformed into linear functions in relation to W , H , D , and P can be expressed as Eq. (2). $a, b, c, \dots, j$ are multi-dimensional regression model coefficients.

$$\left. \begin{aligned} CP &= \alpha \cdot Fz^2 + \beta \cdot Fz \\ \alpha &= aW + bH + cD + dP + e \\ \beta &= fW + gH + hD + iP + j \end{aligned} \right\} \quad (2)$$

Here,

W : Tread width, mm

H : Aspect ratio, %

D : Rim diameter, inch

P : Inflation pressure, kPa

Fz : Normal load, kN

$a, b, \dots, j$: Coefficients of model

Next, the coefficients $a, b, c, \dots, j$ were identified by means of maximum likelihood estimation from CP_i, W_i, H_i, D_i, P_i , and Fz_i in test data. Equation (3) gives the error function of this model, J , for n units of test data.

$$\begin{aligned} J &= \sum_{i=1}^n \{CP_i - CP(a, b, c, d, e, f, g, h, i, j/W_i, H_i, D_i, P_i, Fz_i)\}^2 \\ &= \sum_{i=1}^n \{CP_i - (aW_i Fz_i^2 + bH_i Fz_i^2 + cD_i Fz_i^2 + dP_i Fz_i^2 + eFz_i^2 \\ &\quad + fW_i Fz_i + gH_i Fz_i + hD_i Fz_i + iP_i Fz_i + jFz_i)\}^2 \end{aligned} \quad (3)$$

In order to determine the multi-dimensional regression coefficients $a, b, \dots, j$ so as to minimize J , 10 linear partial differential equations, in which J is partially differentiated for each coefficient and set at 0 are established simultaneously and solved. Taking the equation for coefficient a as an example:

$$\frac{\partial J}{\partial a} = 0 \rightarrow a = \tilde{a} \left| \frac{\partial J}{\partial a} = 0 \right. \quad (4)$$

The partial differential equation that provides conditions of minimum error is therefore Eq. (5) below. Similarly, when partial differential equations are established simultaneously for coefficients b, c, d, e, f, g, h, i , and j , the linear matrix equation Eq. (6) is obtained. A and b are the numerical matrices obtained when test data is substituted, and it is therefore possible to directly derive the multi-dimensional regression model coefficient x from these matrices.

$$\frac{\partial J}{\partial a} = \frac{\partial}{\partial a} \sum_{i=1}^n \left[CP_i - (aW_i Fz_i^2 + bH_i Fz_i^2 + cD_i Fz_i^2 + dP_i Fz_i^2 + eFz_i^2 + fW_i Fz_i + gH_i Fz_i + hD_i Fz_i + iP_i Fz_i + jFz_i) \right]^2 = 0 \quad (5)$$

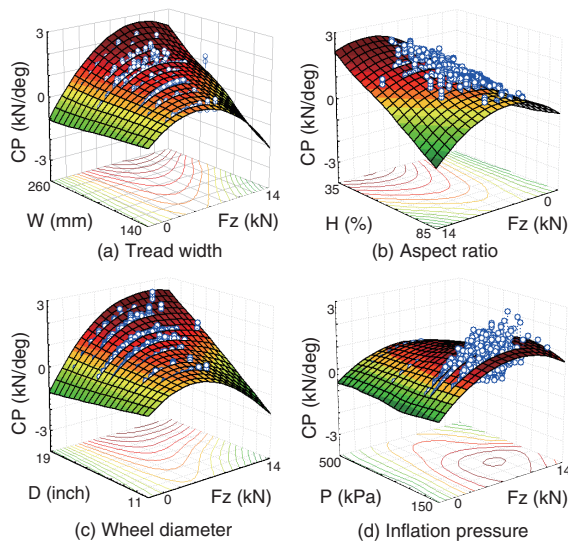


Fig. 7 CP contribution to Fz and tire size parameters

$$Ax = b, \therefore x = A^{-1}b \quad (6)$$

$$A = \begin{bmatrix} \sum W_i^2 Fz_i^4 & \sum W_i H_i Fz_i^4 & \sum W_i D_i Fz_i^4 & \sum W_i P_i Fz_i^4 & \sum W_i Fz_i^4 & \sum W_i^2 Fz_i^3 & \sum W_i H_i Fz_i^3 & \sum W_i D_i Fz_i^3 & \sum W_i P_i Fz_i^3 & \sum W_i Fz_i^3 \\ \sum W_i H_i Fz_i^4 & \sum H_i^2 Fz_i^4 & \sum H_i D_i Fz_i^4 & \sum H_i P_i Fz_i^4 & \sum H_i Fz_i^4 & \sum W_i H_i Fz_i^3 & \sum H_i^2 Fz_i^3 & \sum H_i D_i Fz_i^3 & \sum H_i P_i Fz_i^3 & \sum H_i Fz_i^3 \\ \sum W_i D_i Fz_i^4 & \sum H_i D_i Fz_i^4 & \sum D_i^2 Fz_i^4 & \sum D_i P_i Fz_i^4 & \sum D_i Fz_i^4 & \sum W_i D_i Fz_i^3 & \sum H_i D_i Fz_i^3 & \sum D_i^2 Fz_i^3 & \sum D_i P_i Fz_i^3 & \sum D_i Fz_i^3 \\ \sum W_i P_i Fz_i^4 & \sum H_i P_i Fz_i^4 & \sum D_i P_i Fz_i^4 & \sum P_i^2 Fz_i^4 & \sum P_i Fz_i^4 & \sum W_i P_i Fz_i^3 & \sum H_i P_i Fz_i^3 & \sum D_i P_i Fz_i^3 & \sum P_i^2 Fz_i^3 & \sum P_i Fz_i^3 \\ \sum W_i Fz_i^4 & \sum H_i Fz_i^4 & \sum D_i Fz_i^4 & \sum P_i Fz_i^4 & \sum Fz_i^4 & \sum W_i Fz_i^3 & \sum H_i Fz_i^3 & \sum D_i Fz_i^3 & \sum P_i Fz_i^3 & \sum Fz_i^3 \\ \sum W_i^2 Fz_i^3 & \sum W_i H_i Fz_i^3 & \sum W_i D_i Fz_i^3 & \sum W_i P_i Fz_i^3 & \sum W_i Fz_i^3 & \sum W_i^2 Fz_i^2 & \sum W_i H_i Fz_i^2 & \sum W_i D_i Fz_i^2 & \sum W_i P_i Fz_i^2 & \sum W_i Fz_i^2 \\ \sum W_i H_i Fz_i^3 & \sum H_i^2 Fz_i^3 & \sum H_i D_i Fz_i^3 & \sum H_i P_i Fz_i^3 & \sum H_i Fz_i^3 & \sum W_i H_i Fz_i^2 & \sum H_i^2 Fz_i^2 & \sum H_i D_i Fz_i^2 & \sum H_i P_i Fz_i^2 & \sum H_i Fz_i^2 \\ \sum W_i D_i Fz_i^3 & \sum H_i D_i Fz_i^3 & \sum D_i^2 Fz_i^3 & \sum D_i P_i Fz_i^3 & \sum D_i Fz_i^3 & \sum W_i D_i Fz_i^2 & \sum H_i D_i Fz_i^2 & \sum D_i^2 Fz_i^2 & \sum D_i P_i Fz_i^2 & \sum D_i Fz_i^2 \\ \sum W_i P_i Fz_i^3 & \sum H_i P_i Fz_i^3 & \sum D_i P_i Fz_i^3 & \sum P_i^2 Fz_i^3 & \sum P_i Fz_i^3 & \sum W_i P_i Fz_i^2 & \sum H_i P_i Fz_i^2 & \sum D_i P_i Fz_i^2 & \sum P_i^2 Fz_i^2 & \sum P_i Fz_i^2 \\ \sum W_i Fz_i^3 & \sum H_i Fz_i^3 & \sum D_i Fz_i^3 & \sum P_i Fz_i^3 & \sum Fz_i^3 & \sum W_i Fz_i^2 & \sum H_i Fz_i^2 & \sum D_i Fz_i^2 & \sum P_i Fz_i^2 & \sum Fz_i^2 \end{bmatrix}$$

$$x = \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \\ i \\ j \end{bmatrix}, \quad b = \begin{bmatrix} -\sum W_i Fz_i^2 CP_i \\ -\sum H_i Fz_i^2 CP_i \\ -\sum D_i Fz_i^2 CP_i \\ -\sum P_i Fz_i^2 CP_i \\ -\sum Fz_i^2 CP_i \\ -\sum W_i Fz_i CP_i \\ -\sum H_i Fz_i CP_i \\ -\sum D_i Fz_i CP_i \\ -\sum P_i Fz_i CP_i \\ -\sum Fz_i CP_i \end{bmatrix}$$

3.3. Characteristics of Statistical CP Model

Figure 8 shows estimates of CP calculated by varying tire size variables and inflation pressure using the statistical CP model obtained above. With 195/60R15, an inflation pressure of $P=200$ kPa, and a load of $Fz=4$ kN as the benchmark, W , H , D , and P were separately varied with other variables held constant, and the respective contribution of each variable to CP was determined independently.

A comparatively relaxed positive correlation can be observed between H and CP . The single-dimensional regression analysis performed on the test data in Section

3.2 indicated a comparatively strong negative correlation between the two, but this is thought to reflect the fact that most low-profile tires on the market tend towards a broad W and large D , and CP was high as a result of the effect of this tendency. By contrast, in the case of the statistical CP model, which helps to enable multiple factors to be broken down, it is believed that because it is possible to isolate the separate contribution of the rate of flatness of the tires, a different correlation to that demonstrated by the single-dimensional regression analysis was observed.

The results obtained from the statistical CP model accord with the results of the single-dimensional regression analysis conducted in Section 3.2 in that no clear correlation can be observed between inflation pressure, P , and CP . It is believed that this tendency results from the action of multiple factors, including the canceling effect between the increase in CP due to the increased tire stiffness resulting from increased P and the reduction in CP due to the decreased surface area of the tire in direct contact with the road due to the increase in P .

CP and W display a comparatively strong positive correlation, and this correlation quantitatively expresses the increase in CP due to increased tire width. The contribution of D similarly quantifies the effect of increasing the diameter of the tires.

Figure 9 shows estimated values for the load-dependence of CP . As in Fig. 8, Fig. 9 shows the relationship between Fz and CP when (a) W , (b) D , (c) H , and (d) P are separately varied, this time with 205/55R16 and $P=210$ kPa as the benchmark.

Increasing W increases CP from the low-load range. Increasing D increases the external diameter of the tires,

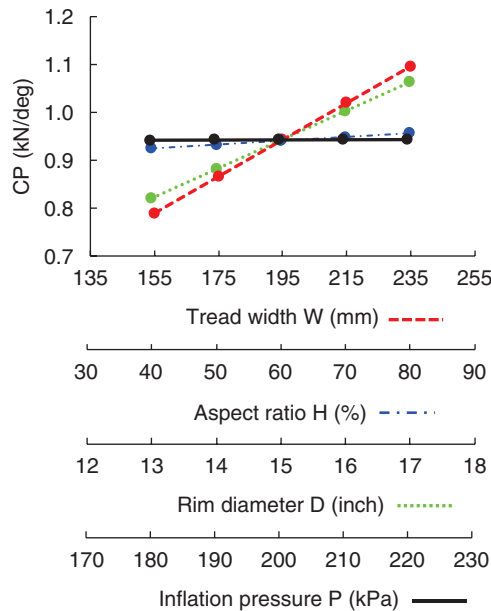


Fig. 8 CP variation by size factor

resulting in a slight reduction in low-load CP and an increase in high-load CP . A reduction in H (flattening the tires) significantly increases CP from the medium- to high-load ranges. An increase in P results in a slight decrease in CP in the low-load range and an increase in the high-load range.

The above characteristics all correspond with already known qualitative data, and it is therefore considered that this model generalizes and quantitatively expresses changes in tire characteristics with changes in tire size and inflation pressure.

3.4. Comparison of Statistical CP Model and Test Data

Test data and estimated values obtained using the statistical CP model were next compared. Figure 10 shows

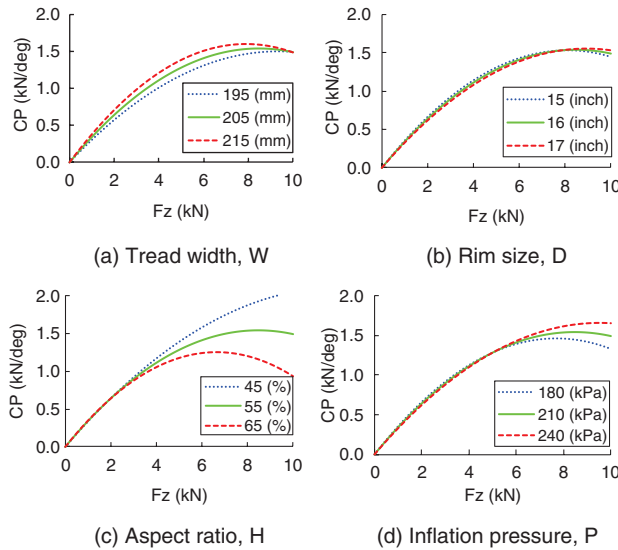


Fig. 9 Relationship between CP and Fz when size parameters varied

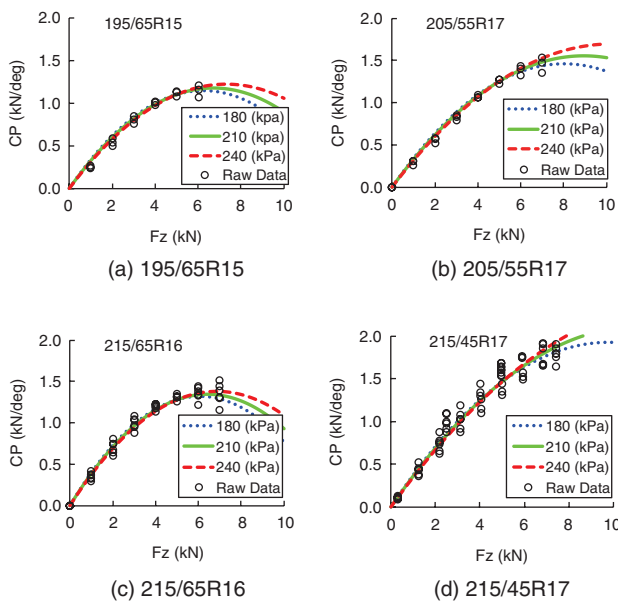


Fig. 10 Experimental data and curves obtained using statistical model

comparisons for four tire sizes. There is some variation in the characteristics displayed by the test data for each size because data for multiple tires of the same size but different type is included, but the statistical tire model reproduces the average characteristics of those tires.

4. Examples of Application of Statistical Tire Model

4.1. Study of Dynamic Performance

This section will look at the application of the statistical CP model to the stability factor, K , and the steering-stability capacity, C_s , as examples of its application to the study of vehicle dynamics. Equation (7), for K , gives an indicator of the vehicle's steer characteristic, while Eq. (9), for C_s , gives one of the indicators that determine Eq. (8), for $\zeta\omega_n$, which expresses steering responsiveness and convergence⁽⁴⁾. Here, an attempt will be made, when K and C_s are changed due to modification of certain vehicle specifications, to return these parameters to their values prior to the changes in specifications by modifying tire size.

$$K = \frac{C_r l_r - C_f l_f}{C_f C_r} \times \frac{m}{L^2} \quad (7)$$

$$\zeta\omega_n = \frac{1}{2V} \left(\frac{C_f + C_r}{m} + \frac{C_f l_f^2 + C_r l_r^2}{I_z} \right) = \frac{C_s}{2V} \quad (8)$$

$$C_s = \frac{C_f + C_r}{m} + \frac{C_f l_f^2 + C_r l_r^2}{I_z} \quad (9)$$

C_f/C_r : Front/Rear axle equivalent CP , N/rad

m : Car mass, kg

WD : Weight distribution to front axle, %

I_z : Yaw moment inertia, kgm^2

L : Wheelbase, m

V : Vehicle speed, m/s

l_f/l_r : Front/rear axle distance from COG, m

ζ : Yaw damping rate, -

ω_n : Yaw natural frequency, sec^{-1}

The case to be considered here will involve a change in specifications from Car A, the benchmark case, to Car B (Table 2).

Figure 11 shows the degree of contribution to K and C_s of the changes in each specification. The arrows show the direction in which each variable increases. When vehicle mass (m : red), yaw inertia moment (I_z : green), and the allocation of weight to the front axle (WD : blue) are increased simultaneously, differences in K and C_s appear between Cars A and B. An appropriate range exists for K and C_s , and the specifications for Car A produce values that basically fall within this range. Here, the potential to realize

Table 2 Car and tire specifications

	Car				Tire			
	L (m)	m (kg)	Iz (kgm ²)	WD (%)	W (mm)	H (%)	D (inch)	P (kPa)
Car A	2.4	950	1400	62.5	175	65	15	210
Car B	2.4	1000	1500	65	-	-	-	-

the same values for K and C_s in Car B as in Car A by means of changing the tire size will be examined.

Figure 12 shows an example of estimates of the degree of contribution of tire size variables in realizing the same level of K and C_s in Car B as in Car A, obtained using the statistical CP model. The arrows indicate the direction in which each variable increases, making it possible to quantitatively grasp the effect of W (blue), H (red), D (green), and P (orange) on K and C_s .

When tire size is changed from 175/65R15 to 185/60R15 under these conditions, the values of K and C_s for Car B, which were previously changed with the modification in the vehicle's specifications, become almost exactly the same as the values for Car A. In actual vehicle developments, other factors are also taken into consideration in determining tire size, but the ability to implement the initial performance design while obtaining a grasp of average tire characteristics

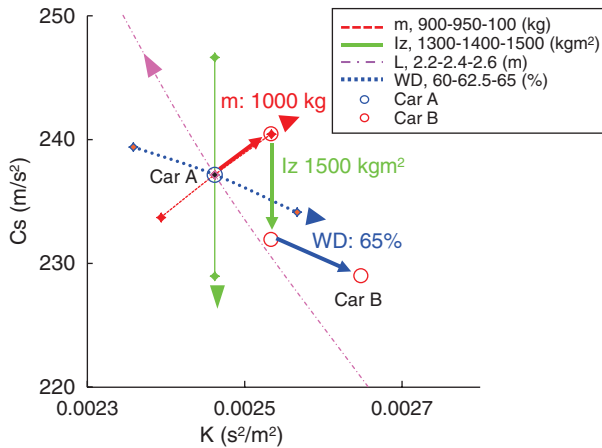


Fig. 11 Effect of changes in car specifications on K and C_s

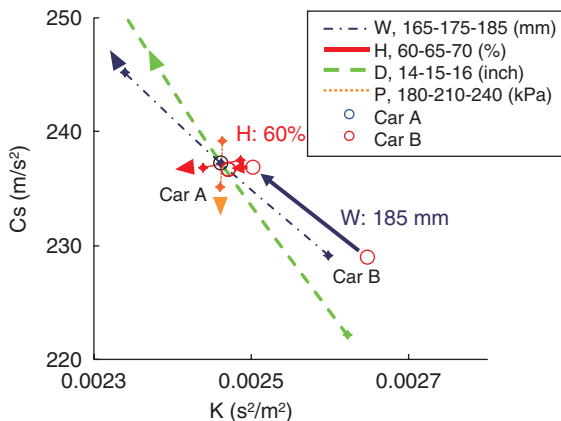


Fig. 12 Effect of tire size parameters on K and C_s

and their effects in this way will make it possible to balance the realization of greater commercial appeal in the finished product with increased efficiency in the development process.

4.2. Study of Dynamic Performance and Ride Comfort

The statistical tire model can be applied to the estimation of tire characteristics other than CP . Figure 13 shows an example in which k_z is modeled at the same time as CP and the effect of tire size on the parameter is studied. k_z is a fundamental tire characteristic that affects ride comfort and other parameters, and it is necessary to conduct studies in order to balance changes in size or specifications to increase CP with ride comfort.

The various color lines in Fig. 13 show the changes in CP and k_z against the benchmark tire specifications (185/65R15, $P=220$ kPa, $F_z=4.5$ kN; the central black point in the graph) when W , H , D , P , and F_z are individually increased and decreased with other characteristics held steady (the arrows show the direction of increase of each variable). The surrounding points show plots of the patterns generated by the combination of increases and decreases in each parameter.

Balancing increased CP with reduced k_z , moving towards the lower right-hand corner of the graph is the generally desirable direction. In actual practice, however, tire size and specifications are set in line with other constraining conditions. It is possible to determine the combinations of size, inflation pressure and load that help to enable the realization of target CP and k_z from the values of the input variables for points in the area that corresponds to the target characteristics. This makes it possible to obtain multiple candidate tire sizes. Because vehicle developers are also able to determine the degree of contribution of each size parameter at the same time, it is possible to proceed with quantitative studies towards the selection of the optimum tire size from among the candidates, while also taking other factors into consideration.

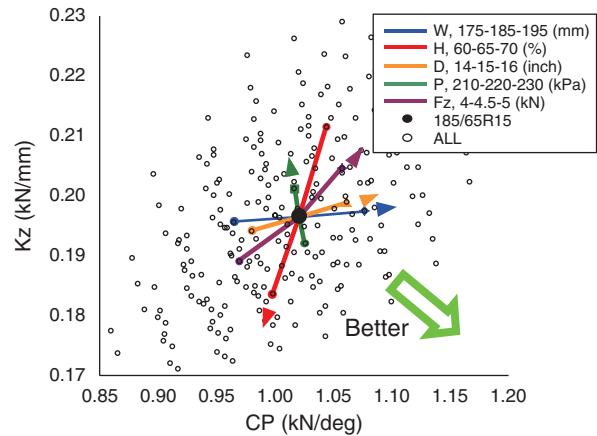


Fig. 13 Variation of CP and k_z when size parameters, inflation pressure and tire load changed

5. Conclusion

A statistical tire model making it possible to quantitatively estimate tire characteristics from tire size and specifications has been developed.

- (1) This tire model makes it possible to estimate tire characteristics for tires of various sizes without individually measuring and modeling the target tires.
- (2) For the modeling method, an experimental model for a single tire is expanded, and a system identification method is used to generate a multi-dimensional approximation equation from a data group encompassing multiple tires.
- (3) The use of this model, which is able to treat changes in tire size, will make it possible to conduct performance design at the initial stage of the development process more accurately and more efficiently.

In future, the authors intend to conduct further measurements of tire data, seeking, in addition to enhancing the physical theory basis of the statistical model, to realize further data accumulation in order to increase the accuracy of model identification, expand the range of applicable tire sizes, and incorporate qualitative variables such as tire material and structure into the model.

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